

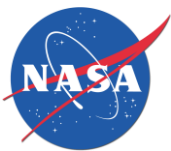
# Ensemble forecasting and initial condition sensitivity for hurricanes

Sharanya J. Majumdar  
RSMAS / University of Miami

<http://orca.rsmas.miami.edu/~majumdar>

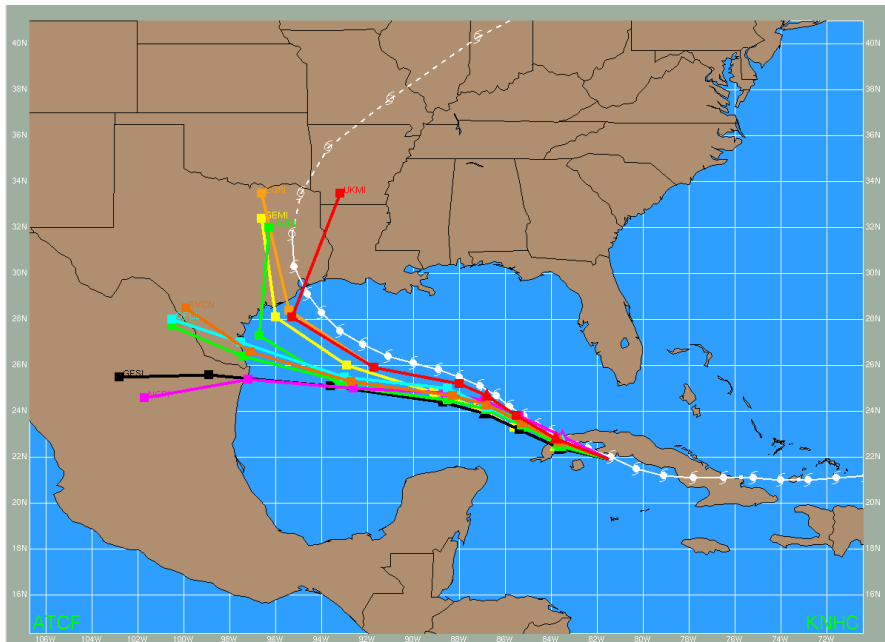
National Weather Center, Norman, OK

October 11<sup>th</sup> 2011



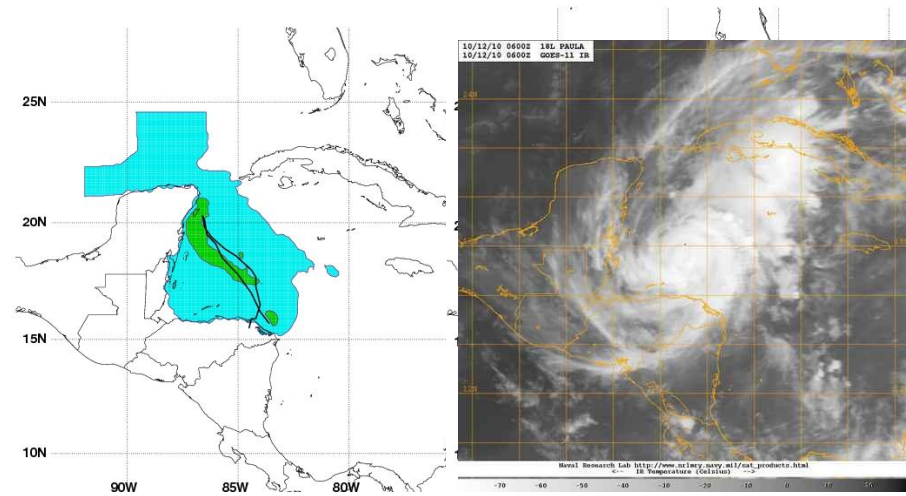
# Where tropical cyclone forecasts go wrong

## Track prediction



Global and regional models

## Formation / structure / intensity prediction



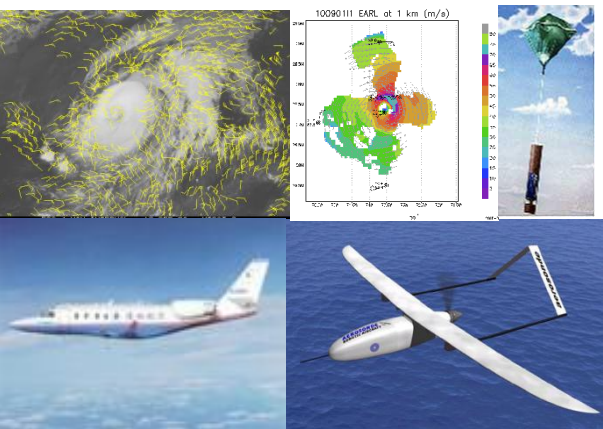
HWRF: Paula  
Monday, 18 UTC

HWRF: Paula  
Tuesday, 06 UTC

Regional models

Why do forecasts possess errors? How do we reduce errors and understand uncertainty?

1. **Errors in the initial conditions**
2. Errors in the model physics and boundary conditions



New  
observational  
data

Data  
Assimilation

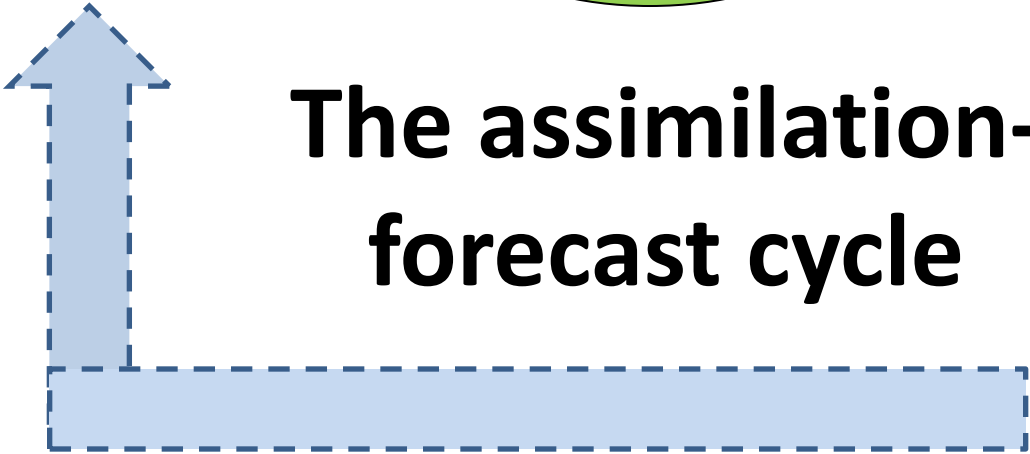
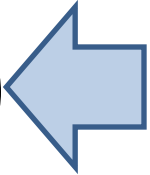
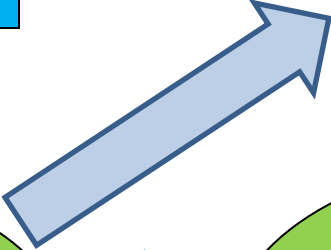
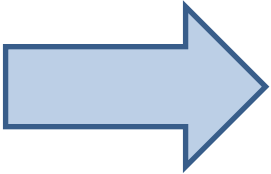
1-12 hr forecast  
'first guess' for  
data assimilation

Model / Ensemble  
initial  
conditions

Adaptive sampling  
strategy?

**The assimilation-  
forecast cycle**

End product:  
Deterministic  
and Probabilistic  
Forecast



# Outline of Seminar

## A. Typhoon Sinlaku (2008)

1. Sensitivity to direct environmental perturbations
2. How do Singular Vectors govern ensemble spread?

## B. Hurricane Ike (2008)

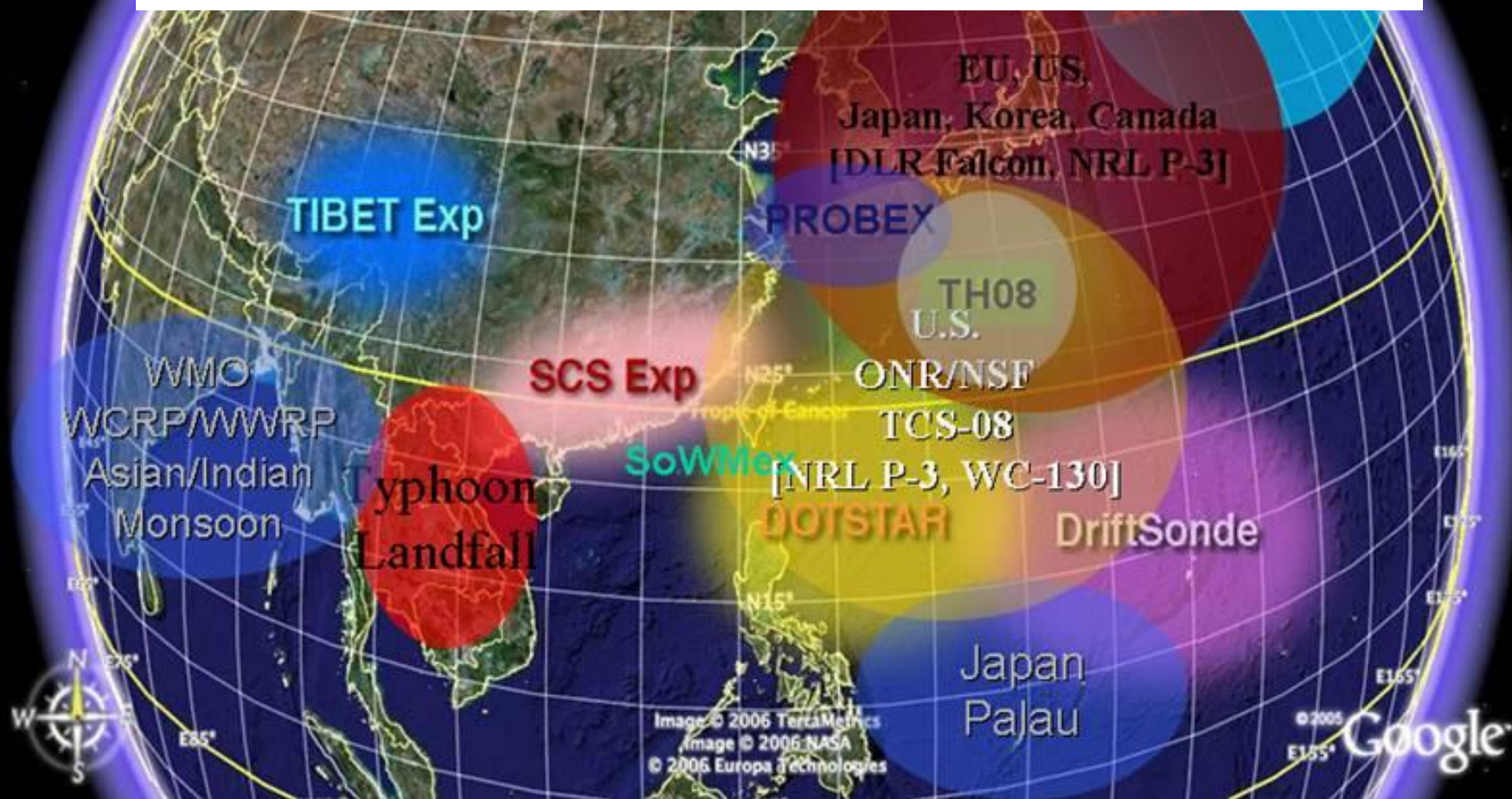
1. Ensemble probabilistic prediction
2. Sensitivity to remote perturbations

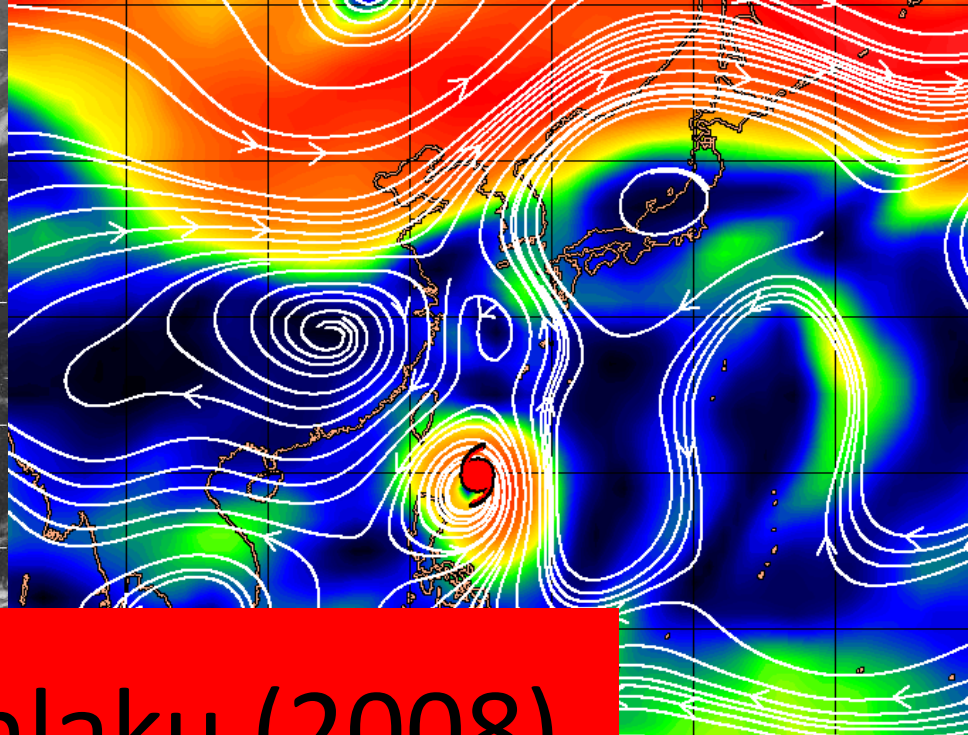
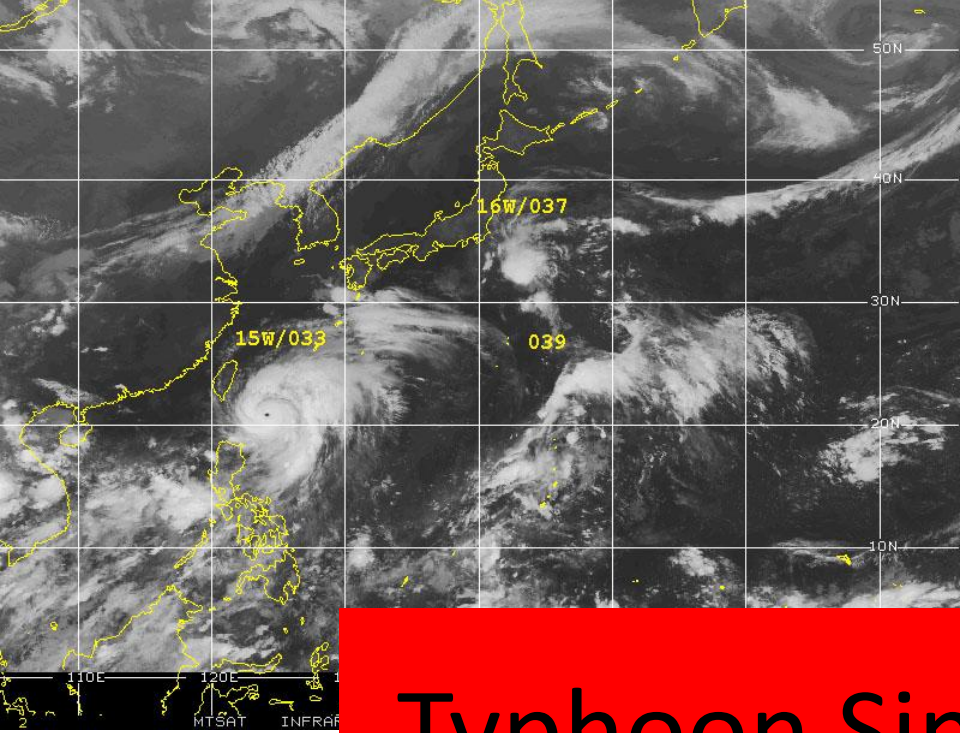
## C. Hurricane Irene (2011)

1. Influence of assimilating special soundings
2. Ensemble prediction of tropical cyclogenesis

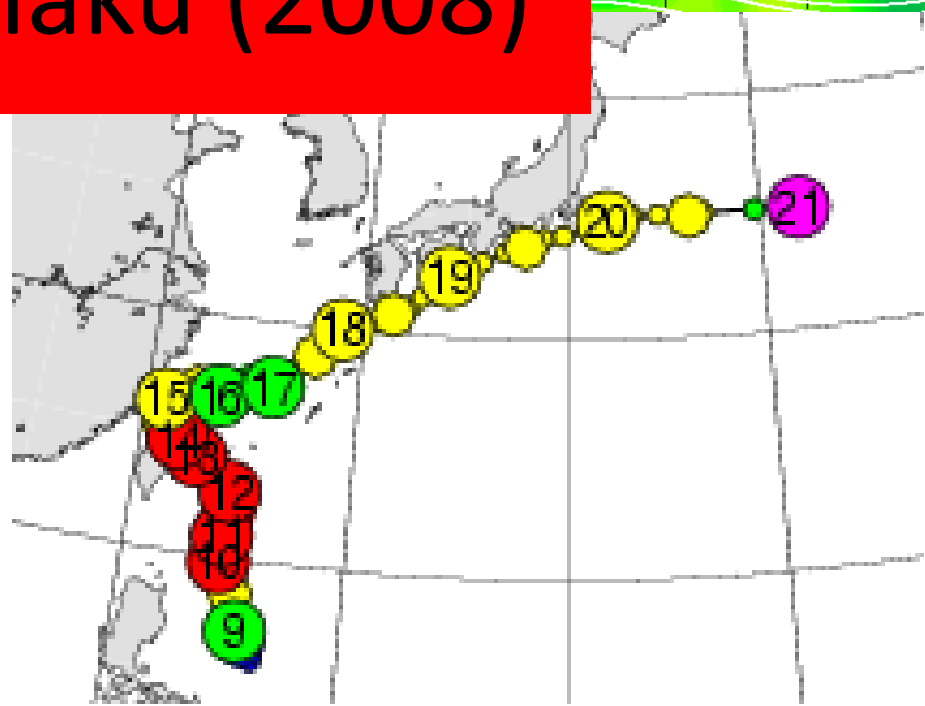
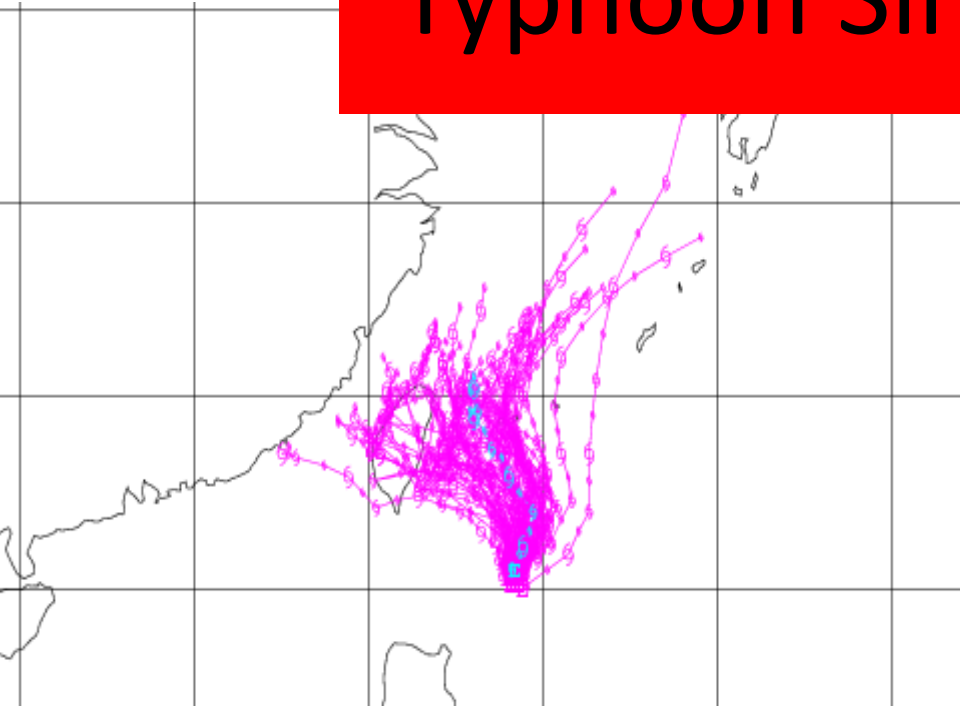
# THORPEX-Pacific Asian Regional Campaign/Tropical Cyclone Structure-08 Experiments and Collaborative Efforts

One Goal: Advancing knowledge and improving the short-range prediction of tropical cyclones over eastern Asia and the western Pacific.



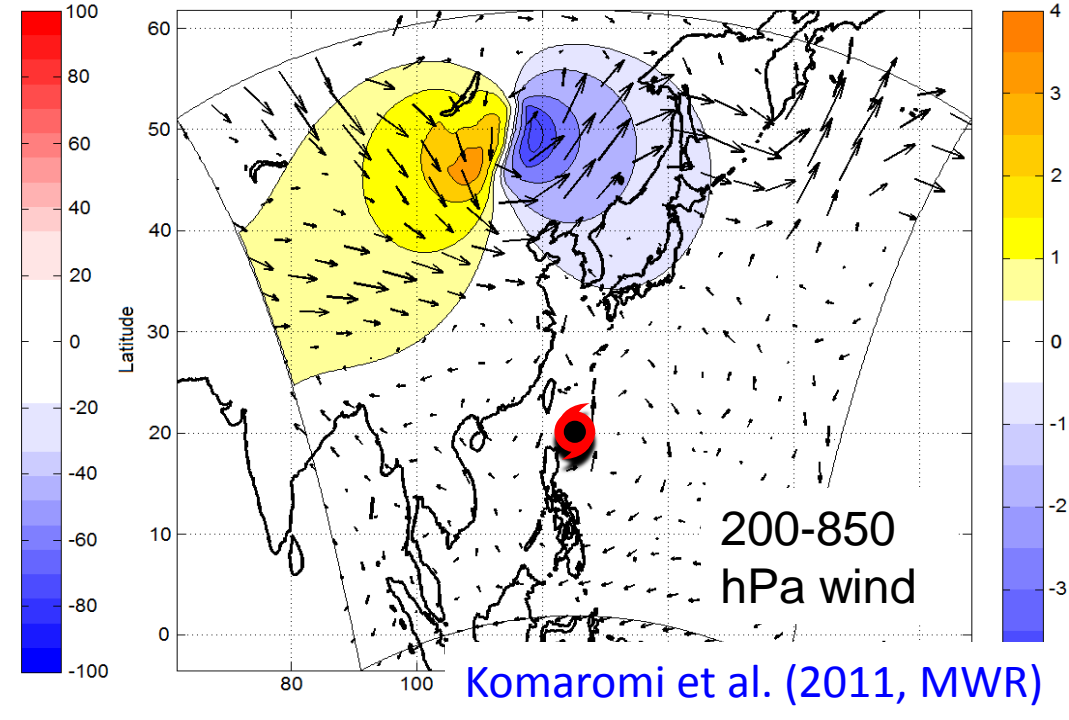
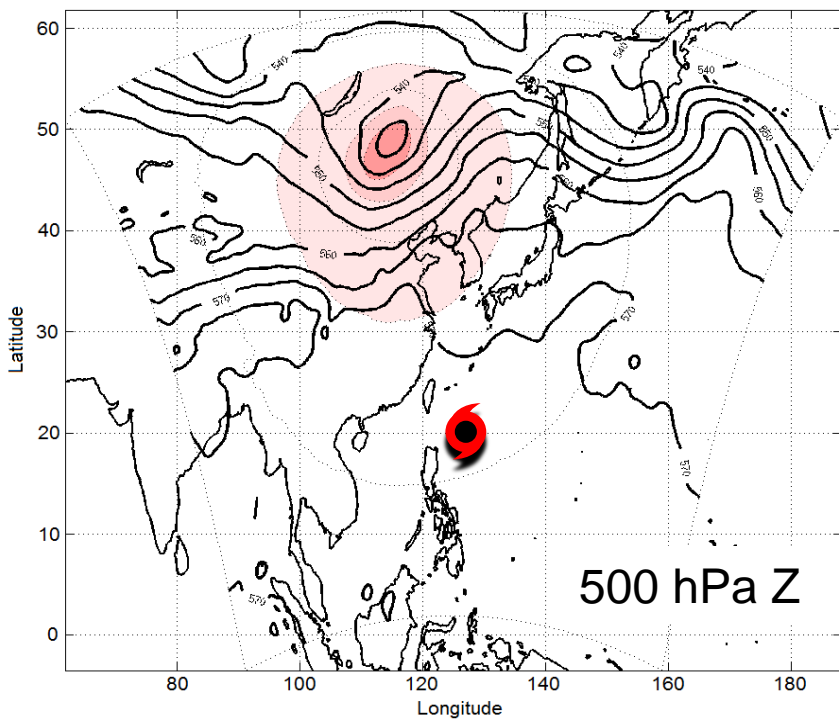
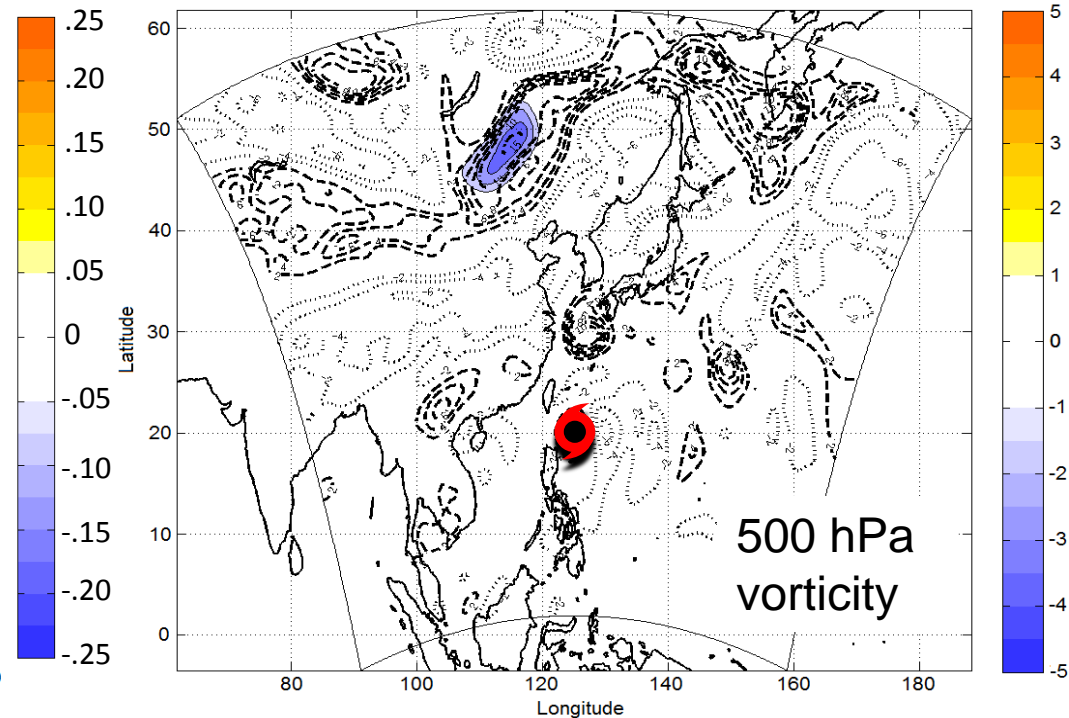
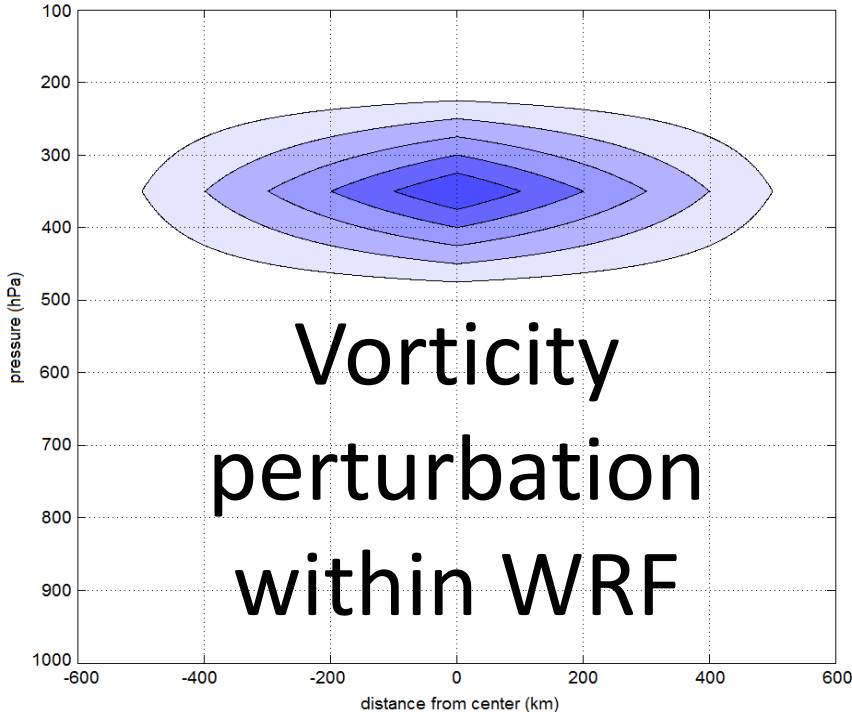


# Typhoon Sinlaku (2008)

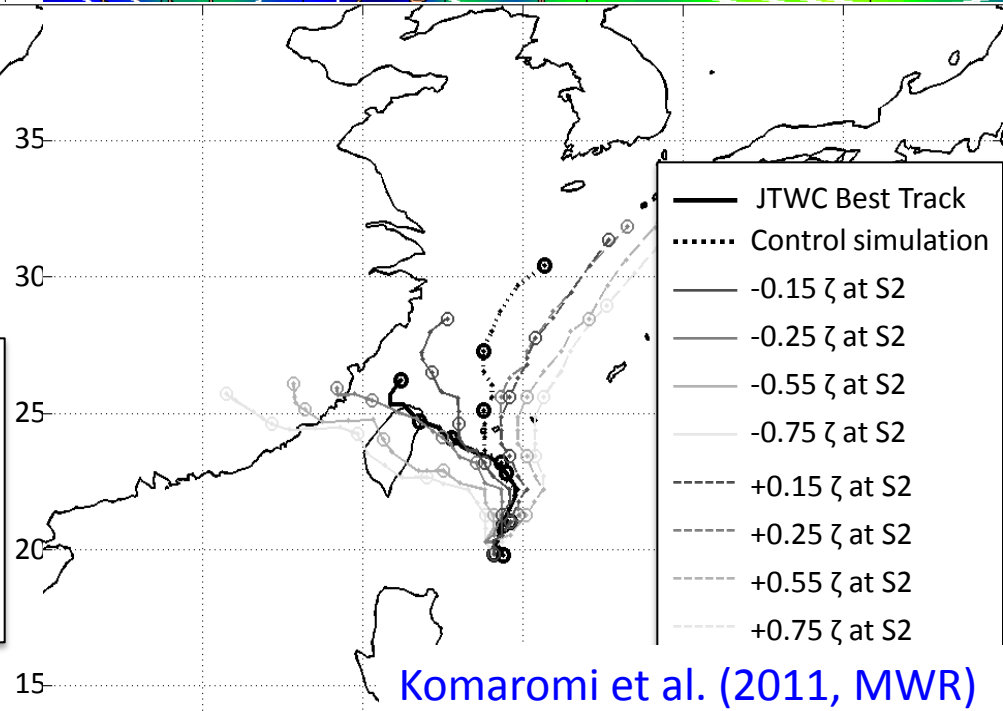
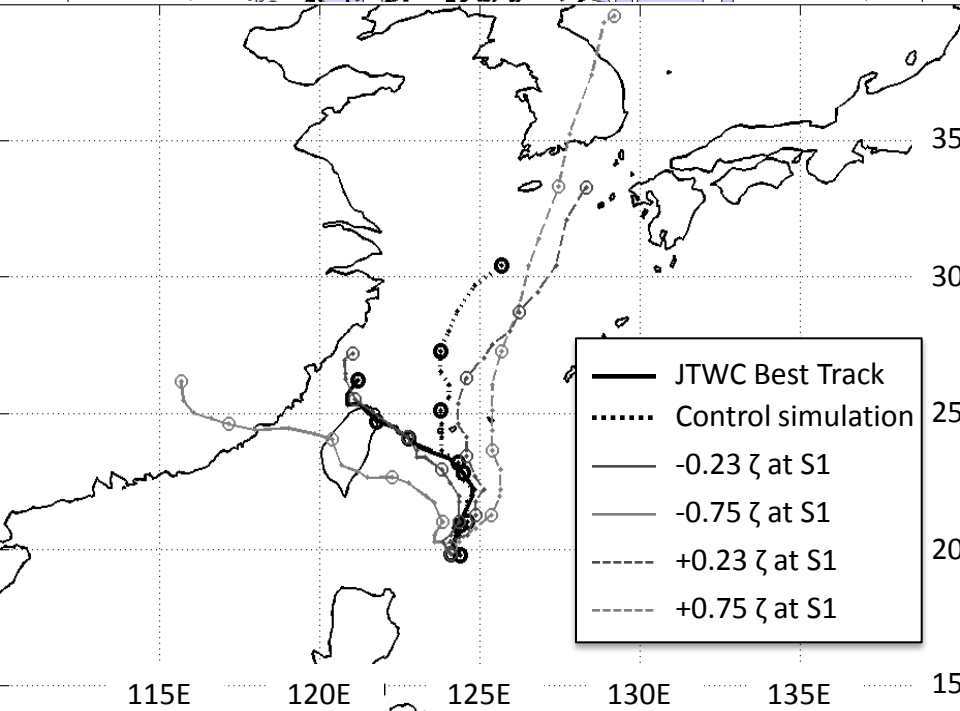
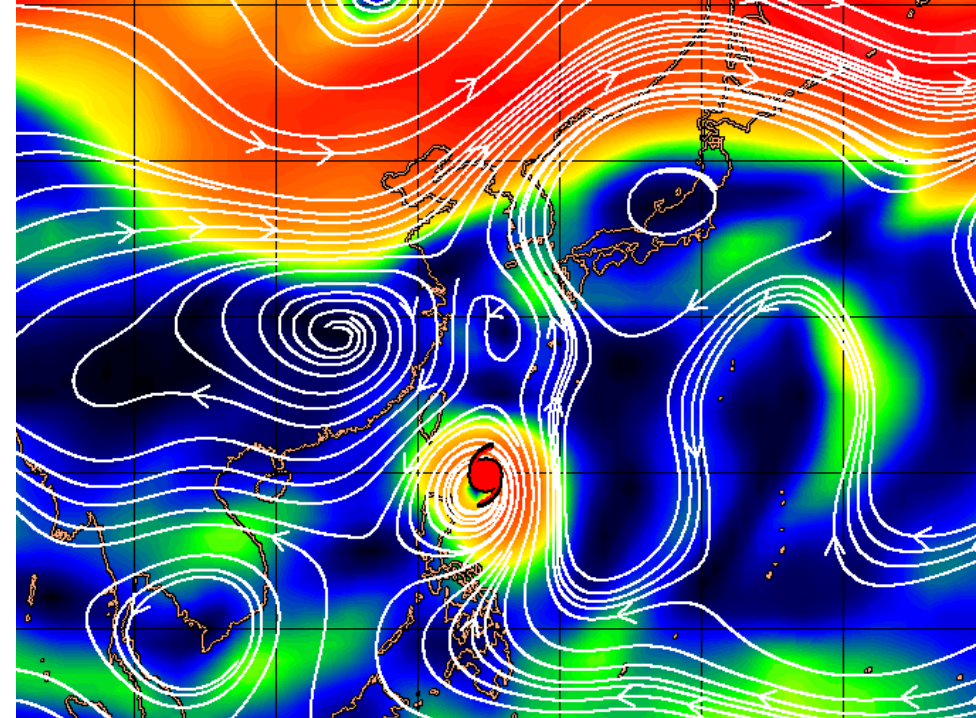
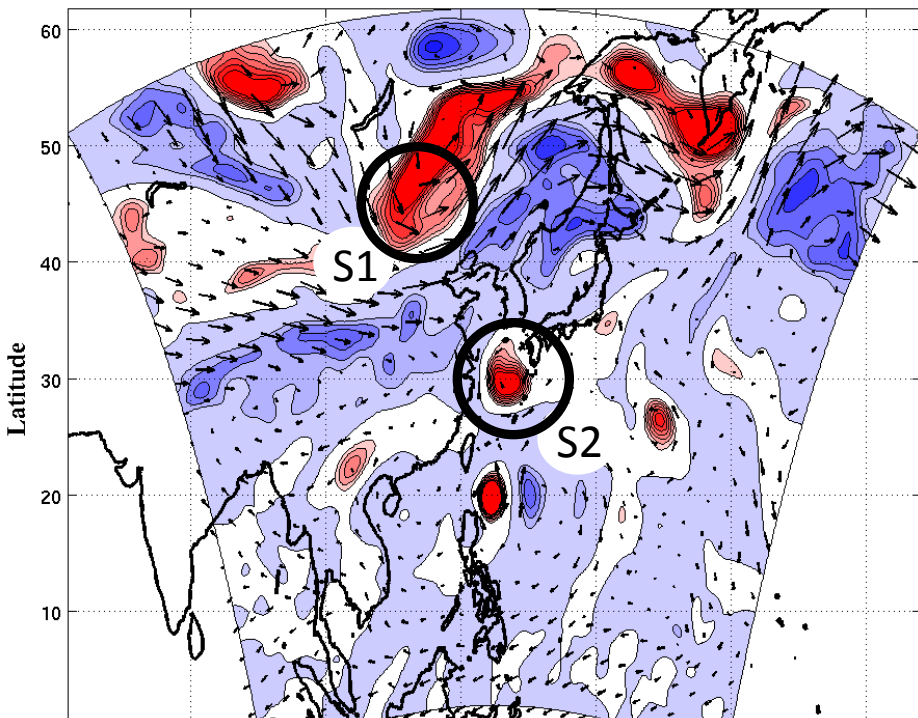


# Sinlaku: Hypotheses

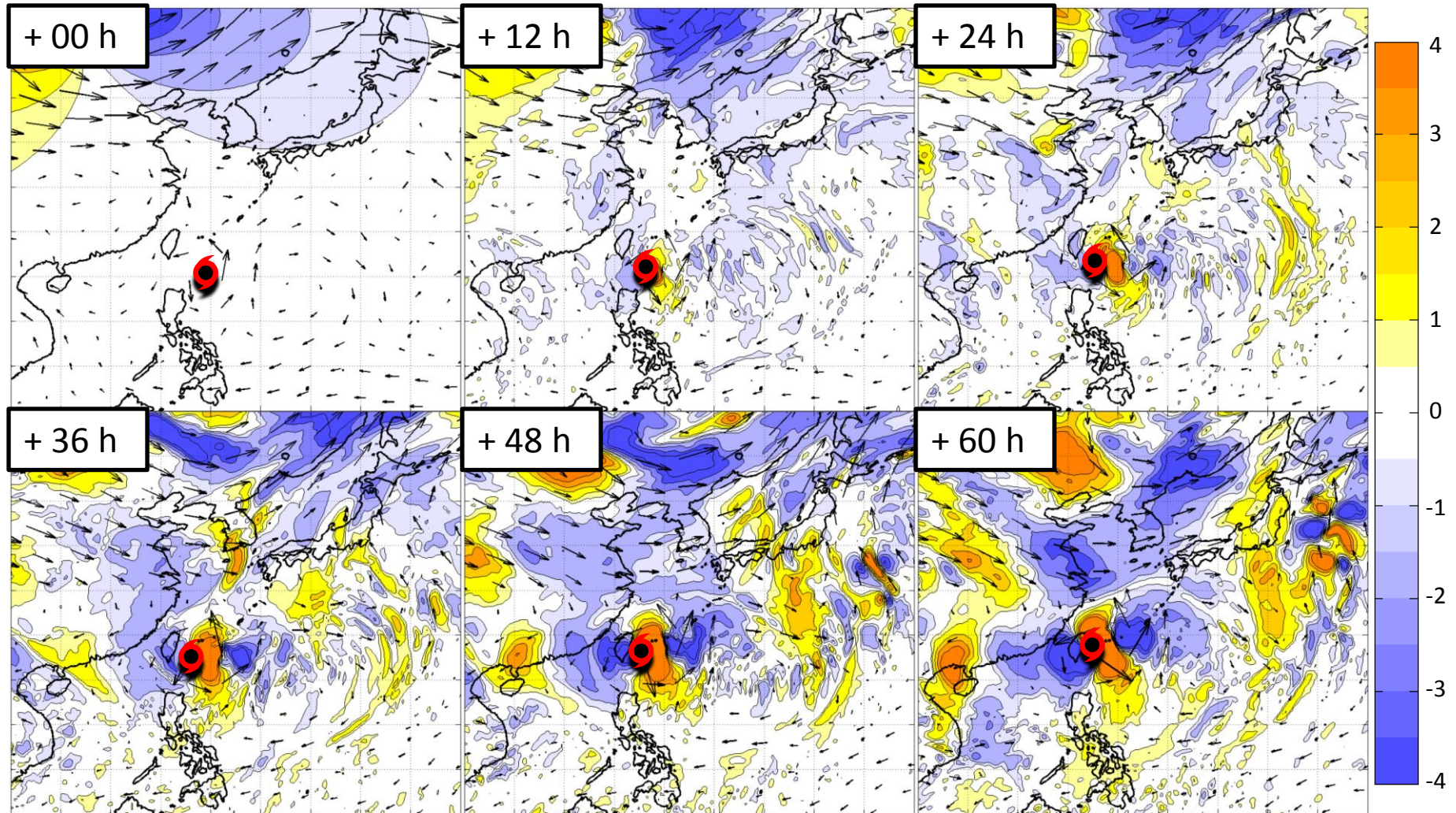
1. TC forecasts are sensitive to perturbations in the synoptic environment.
2. The spreading in TC track forecasts is due to instabilities in the storm and its environment.



Komaromi et al. (2011, MWR)

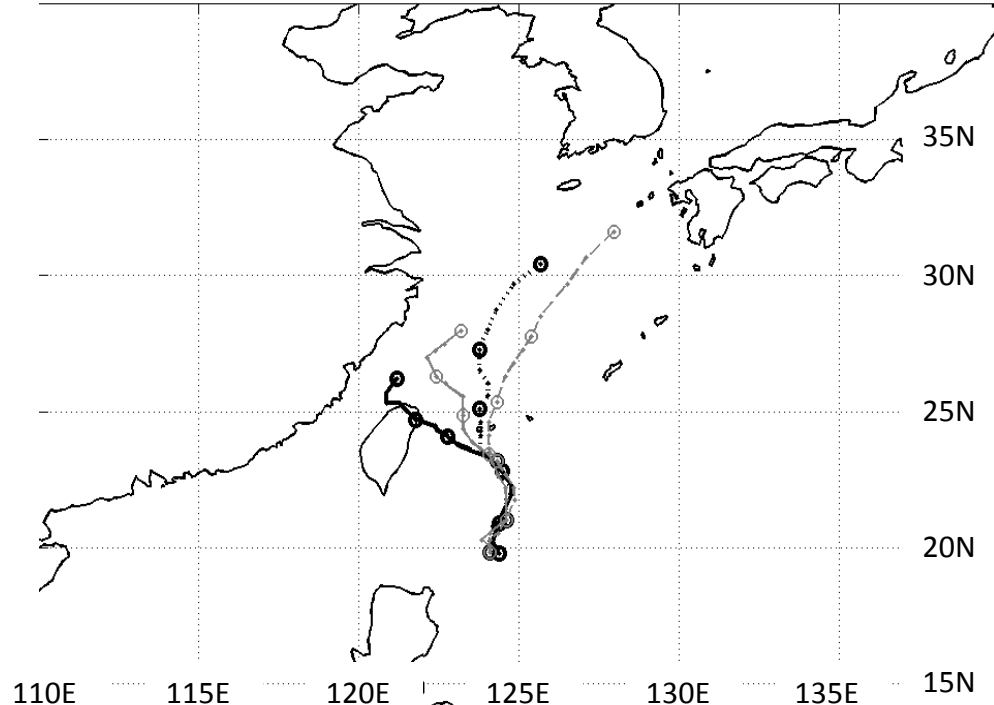
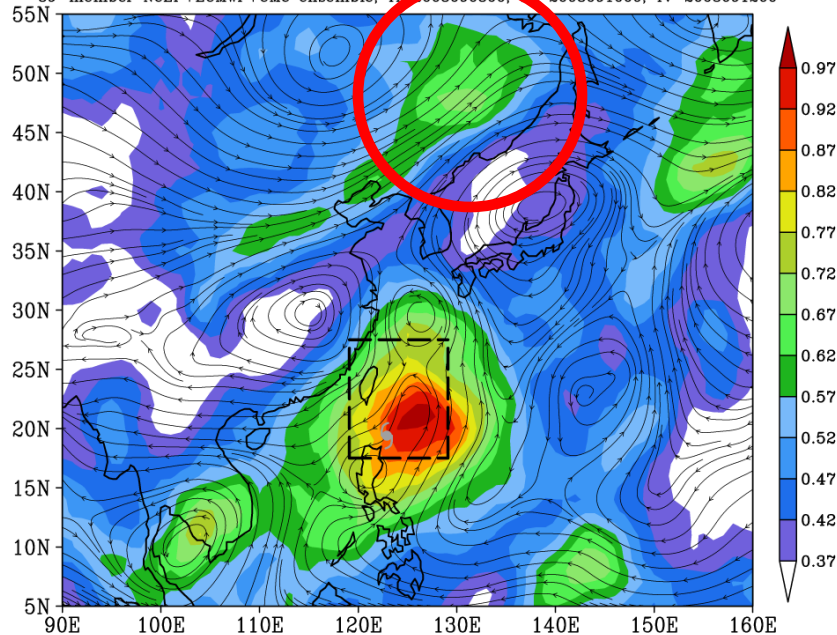


# S1: Impact of weakening mid-latitude trough



# Perturbation to ETKF target

Shading: ETKF reduction in wind forecast error variance due to targeted obs of u,v,T at 850/500/200 hPa  
Contour: ensemble mean streamline at 500 hPa at targeted time  
89-member NCEP+ECMWF+CMC ensemble; Tl=2008090800; Ts=2008091000; Tv=2008091200



Some ETKF targets demonstrate sensitivity.

However, ranking of targets is inconsistent with ranking of targets made by direct perturbations.

# Sinlaku: Results 1

H: TC forecasts are sensitive to perturbations in the synoptic environment

- Yes, even to perturbations of modest strength.
- Moderate weakening of (S1) mid-latitude trough and (S2) neighbouring upper-level low lead to avoidance of premature recurvature → features initialized too strongly?
- More direct method than adaptive sampling methodologies; however, not applicable in real-time.

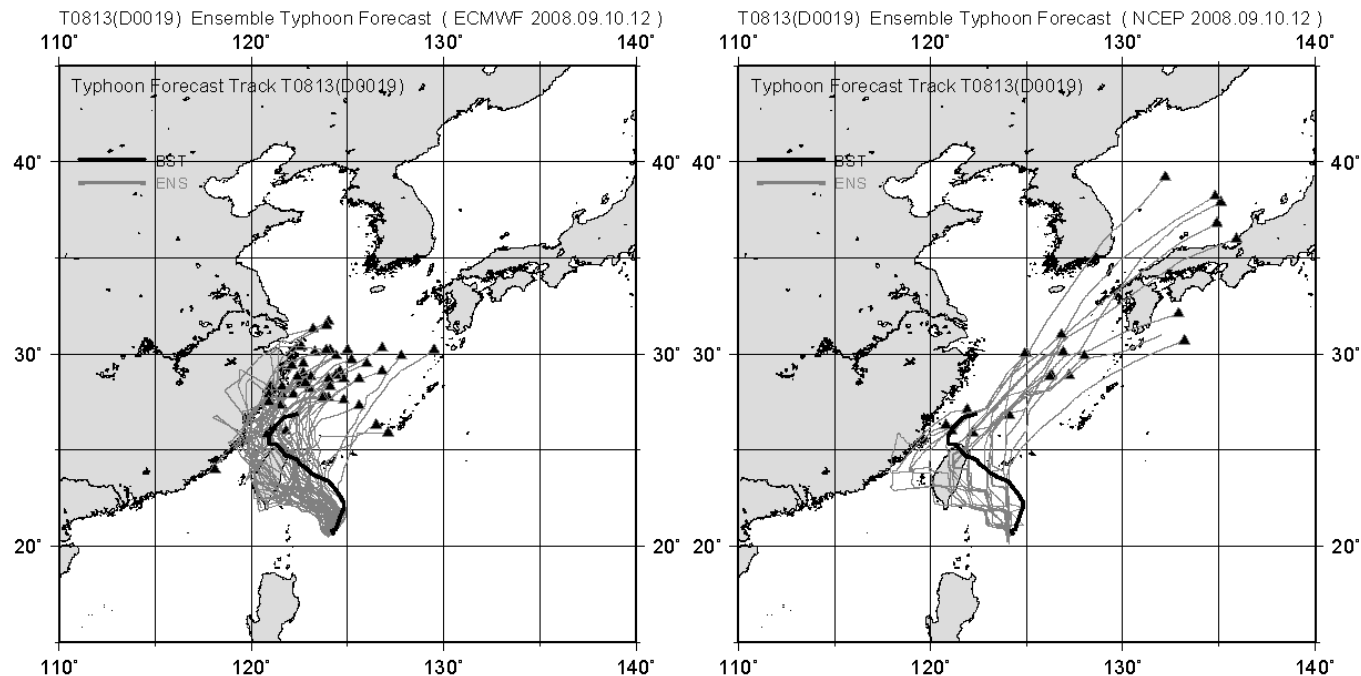
# Sinlaku: Hypotheses

1. TC forecasts are sensitive to perturbations in the synoptic environment.
2. The spreading in TC track forecasts is due to instabilities in the storm and its environment.

# Ensemble prediction systems

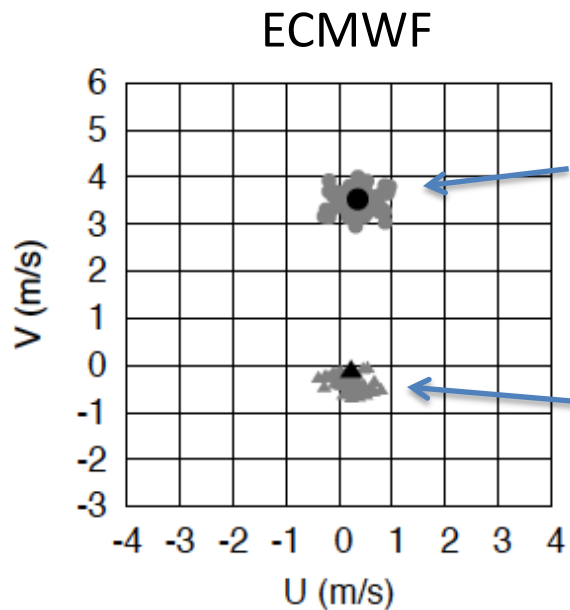
NCEP: use Ensemble Transform to initialize ensemble.

ECMWF: use Singular Vectors to initialize ensemble.



What mechanisms cause the spreading of the ensemble members?

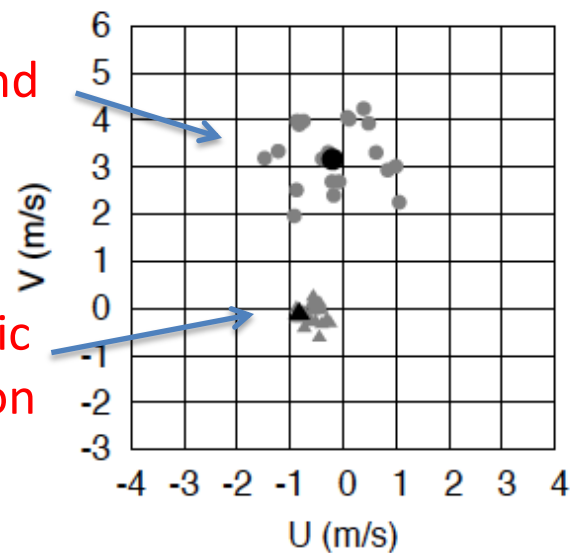
0 h



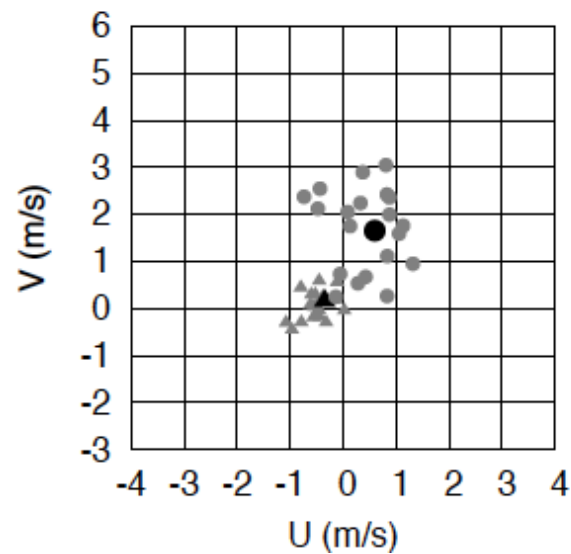
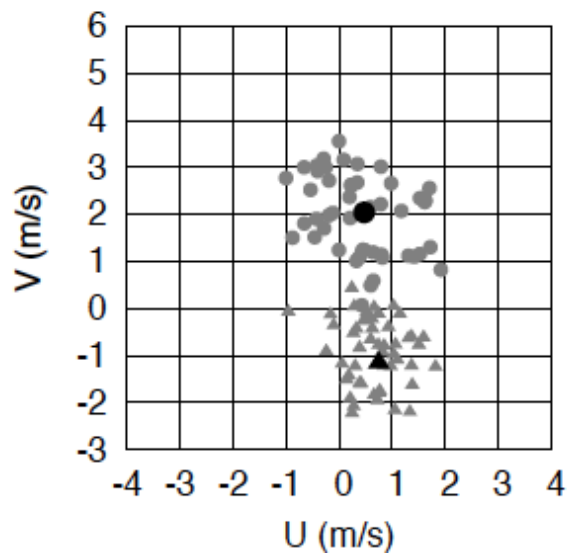
Background steering

Asymmetric propagation

NCEP



12 h



# Singular Vectors

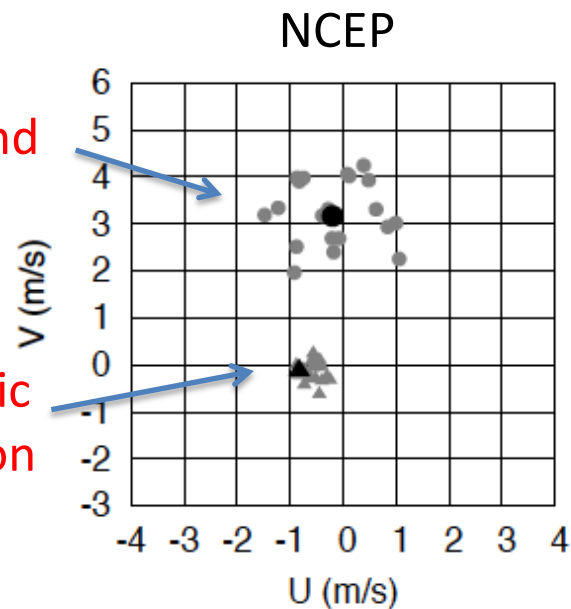
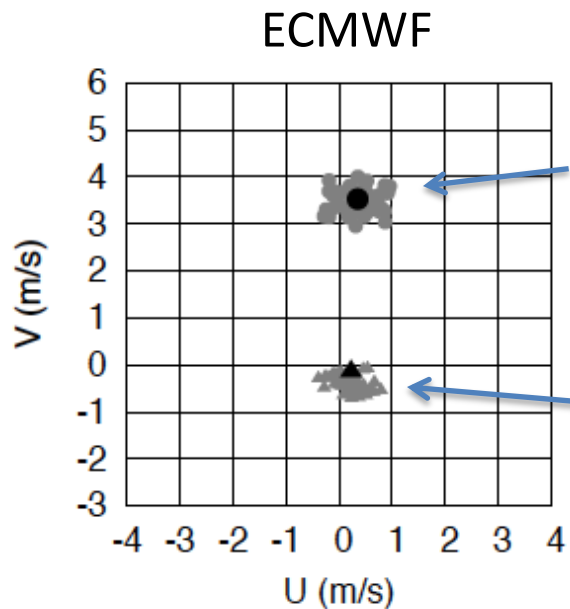
Solve “analysis error covariance optimals” via

$$(\mathbf{GL})^*(\mathbf{P}^v)^{-1}(t_v)(\mathbf{GL})\mathbf{v}_i(t_a) = \sigma_i^2(\mathbf{P}^a)^{-1}(t_a)\mathbf{v}_i(t_a)$$

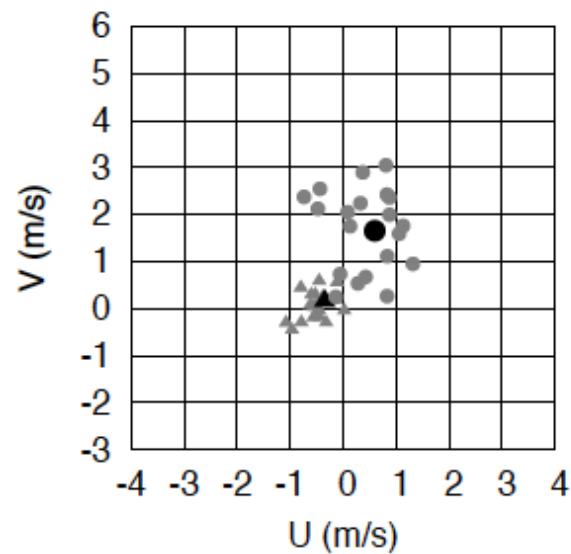
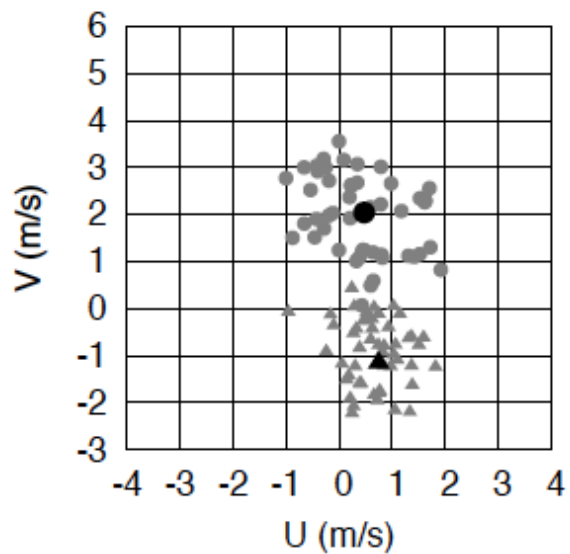
Result: perturbation structures that grow, in a linear sense, to maximize total energy within a verification region around the tropical cyclone.

Add these structures to the ECMWF analysis to obtain a spreading in the forecast tracks.

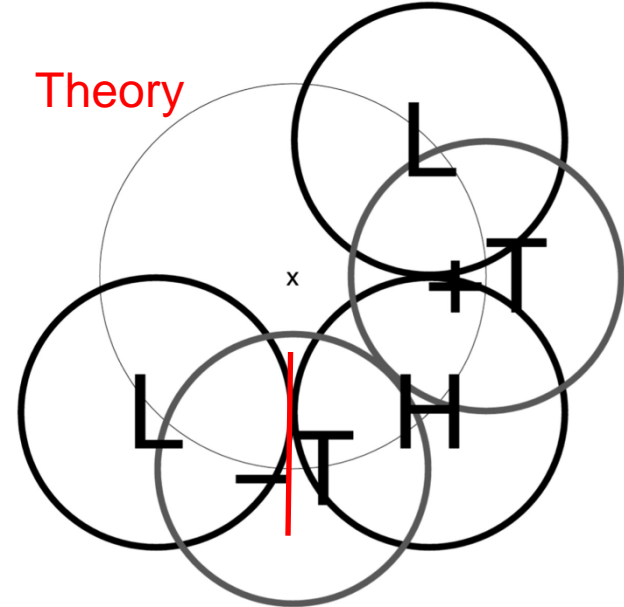
0 h



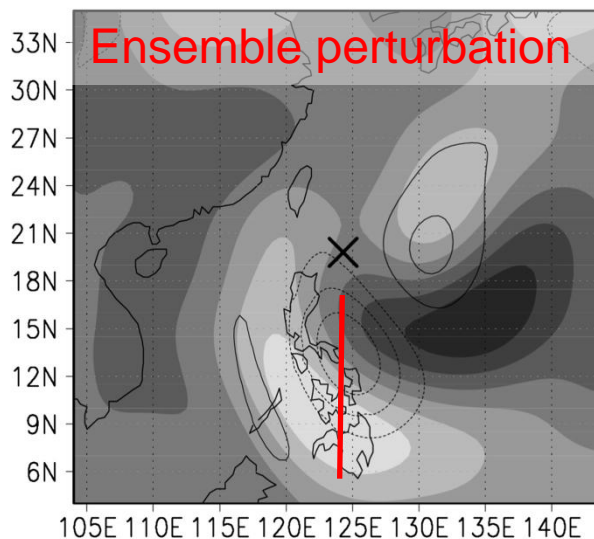
12 h



Theory

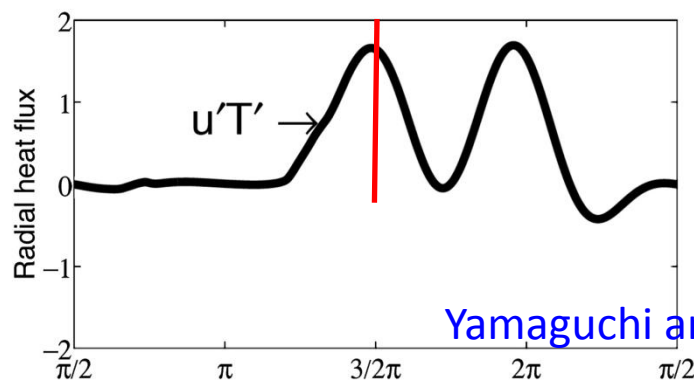
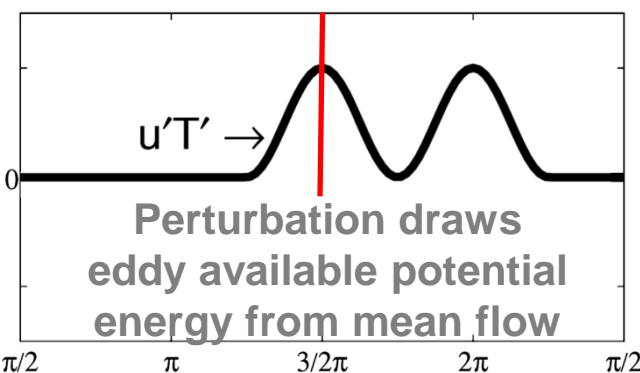
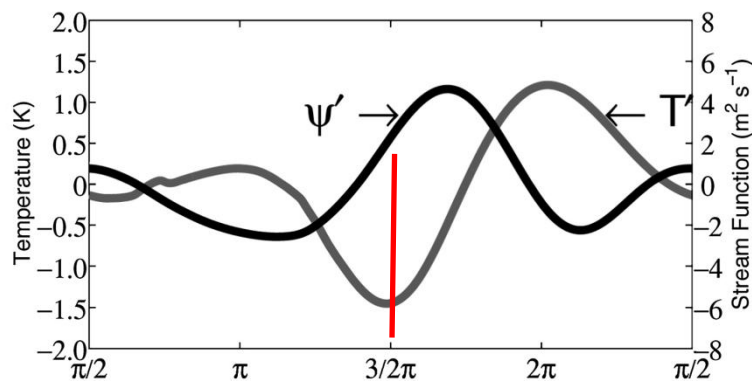
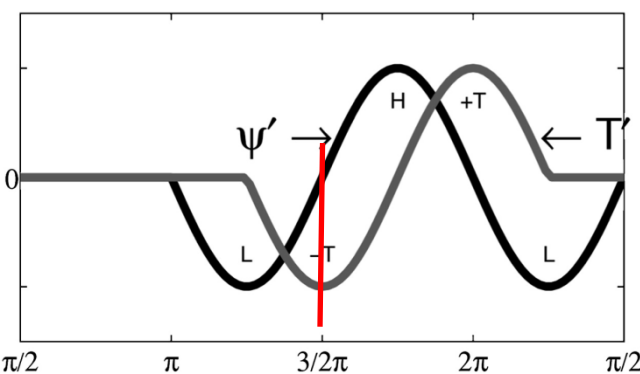


Ensemble perturbation



Shading: Streamfunction  
Contour: Temperature

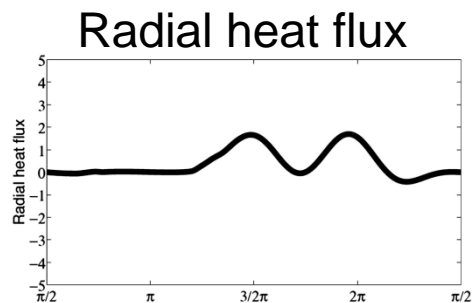
Baroclinic  
instability  
centered  
on the  
vortex



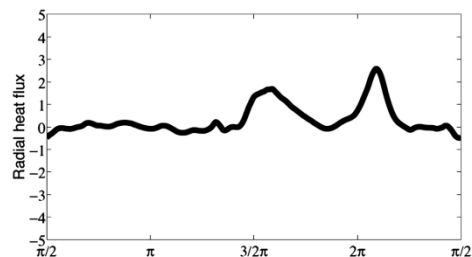
Perturbation draws  
eddy available potential  
energy from mean flow

Yamaguchi and Majumdar (2010, MWR)

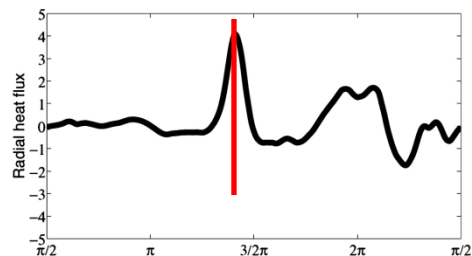
0 h



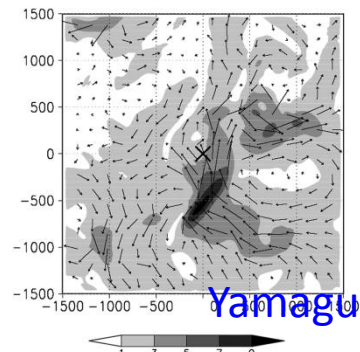
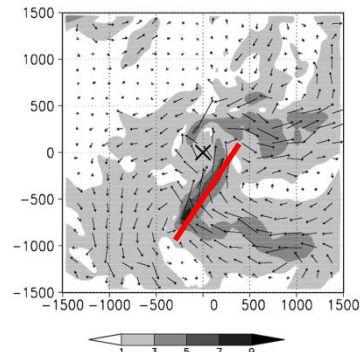
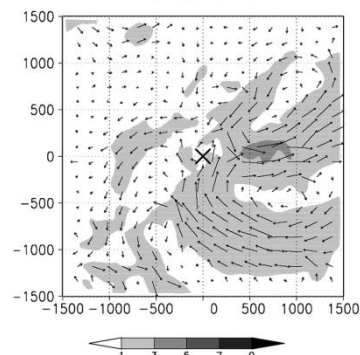
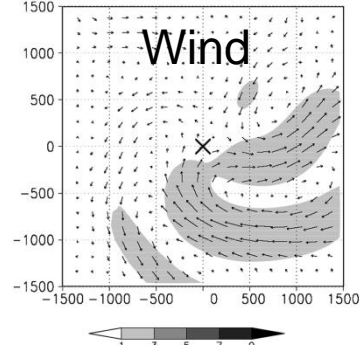
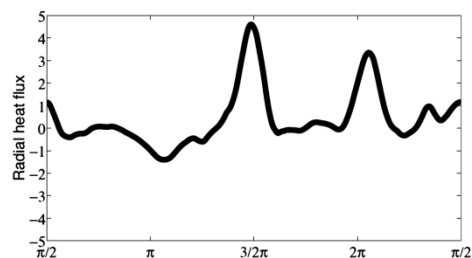
6 h



12 h



18 h

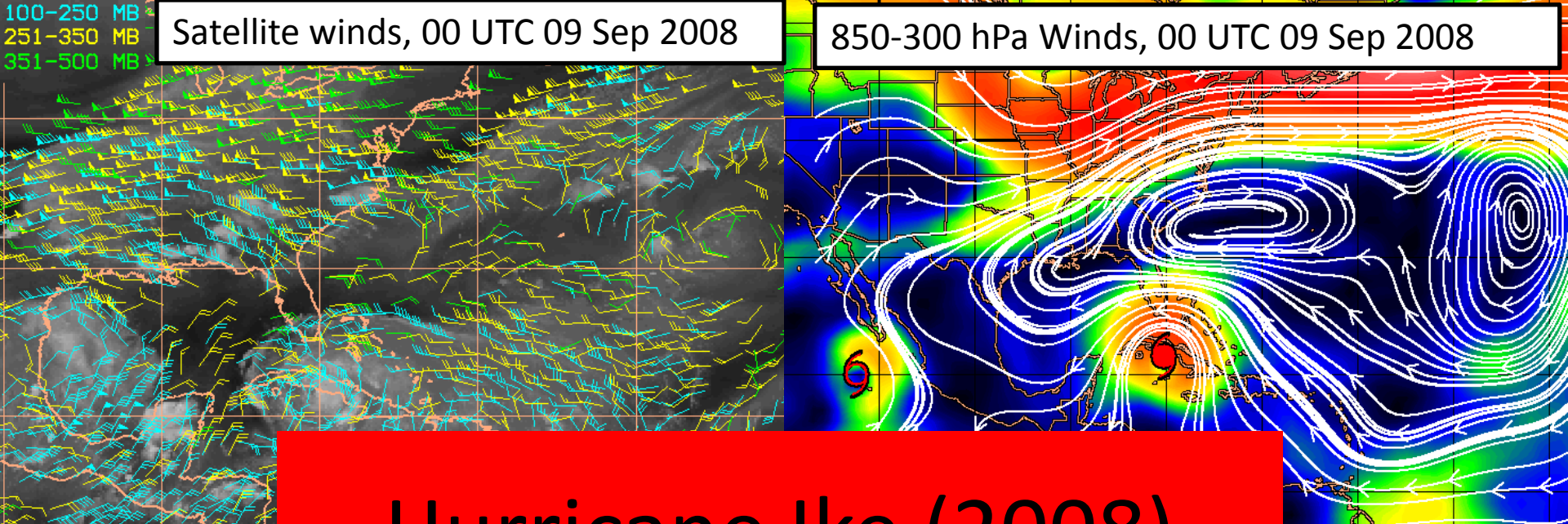


Hypothesis:  
Eddy APE is  
converted into  
EKE  $\rightarrow$  wind  
perturbation  
grows where  
radial heat  
flux is positive

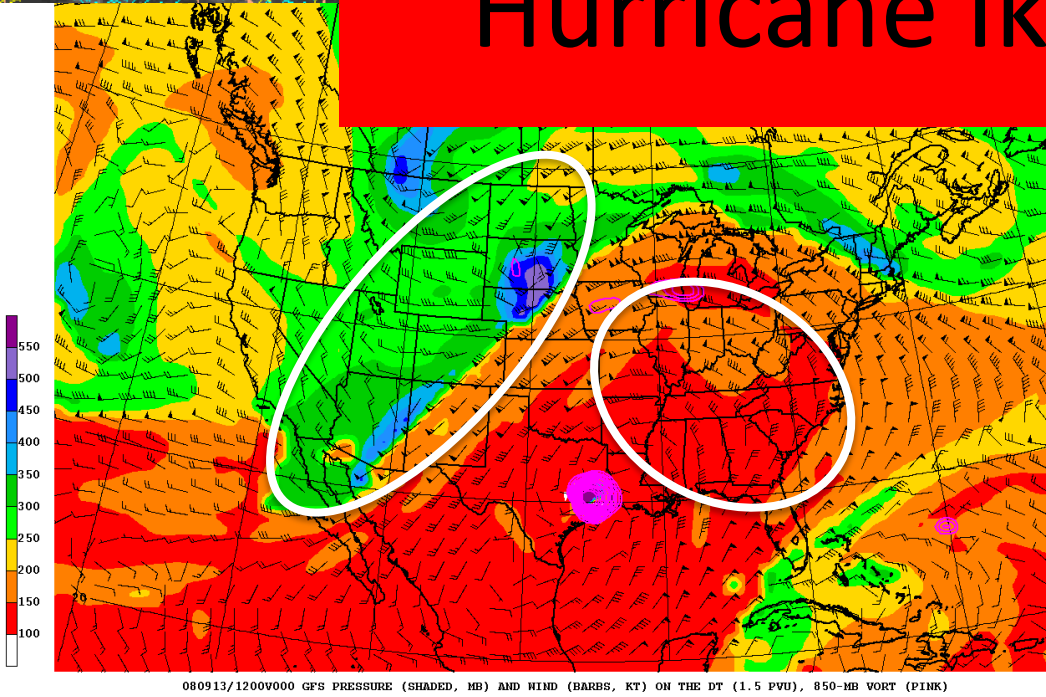
# Sinlaku: Results 2

H: The spreading in TC track forecasts is due to instabilities in the storm and its environment.

- Growth of advection flow of Sinlaku is larger in ECMWF than NCEP.
- Perturbation growth in ECMWF ensemble associated with
  - 1) baroclinic energy conversion in a vortex,
  - 2) baroclinic energy conversion in midlatitude waves,
  - 3) barotropic energy conversion in a vortex.



# Hurricane Ike (2008)

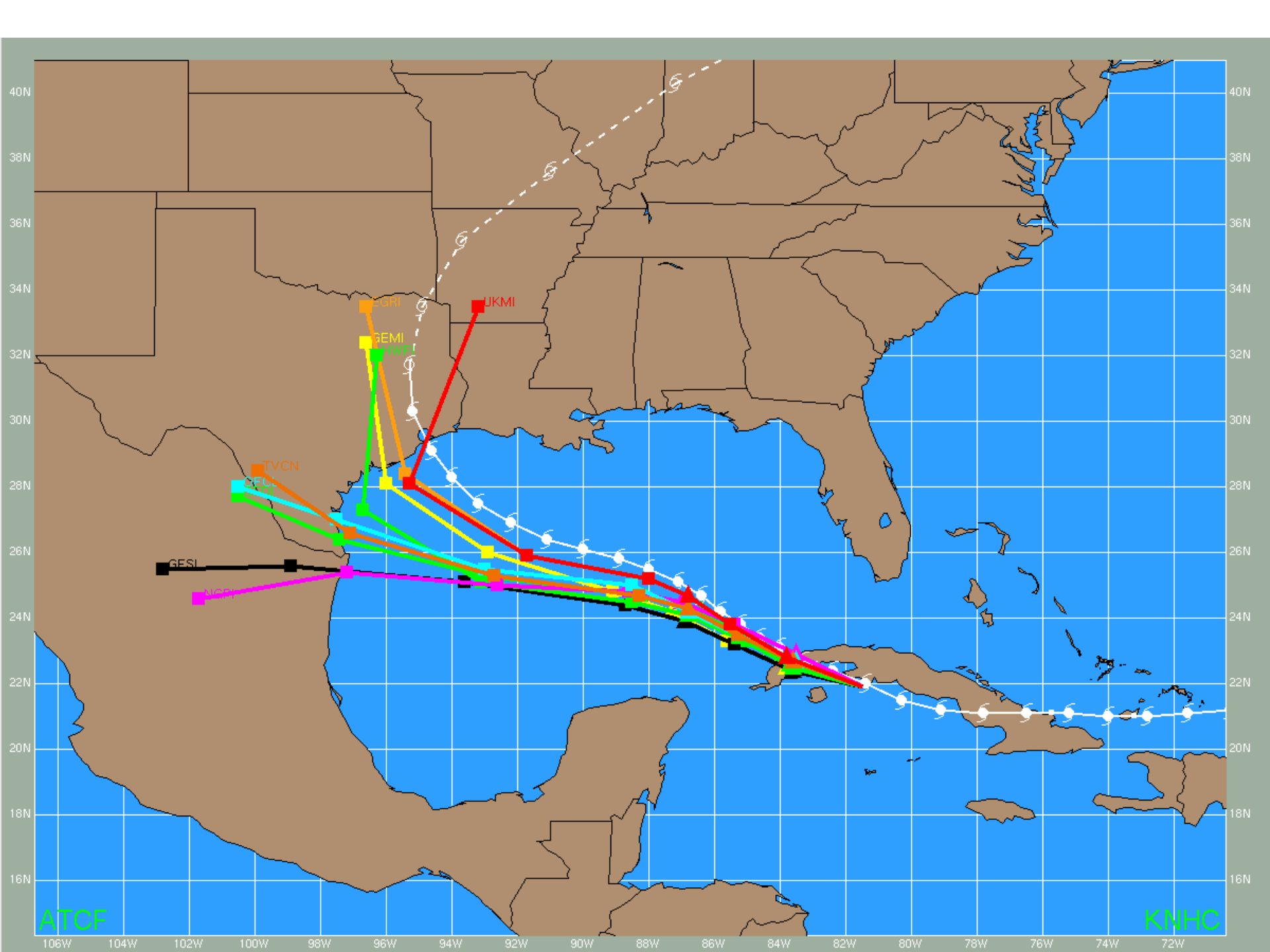


12 UTC 13 Sep 2008

**Zonal flow over CONUS amplified as two tropopause disturbances moved into western North America on 9 Sep.**

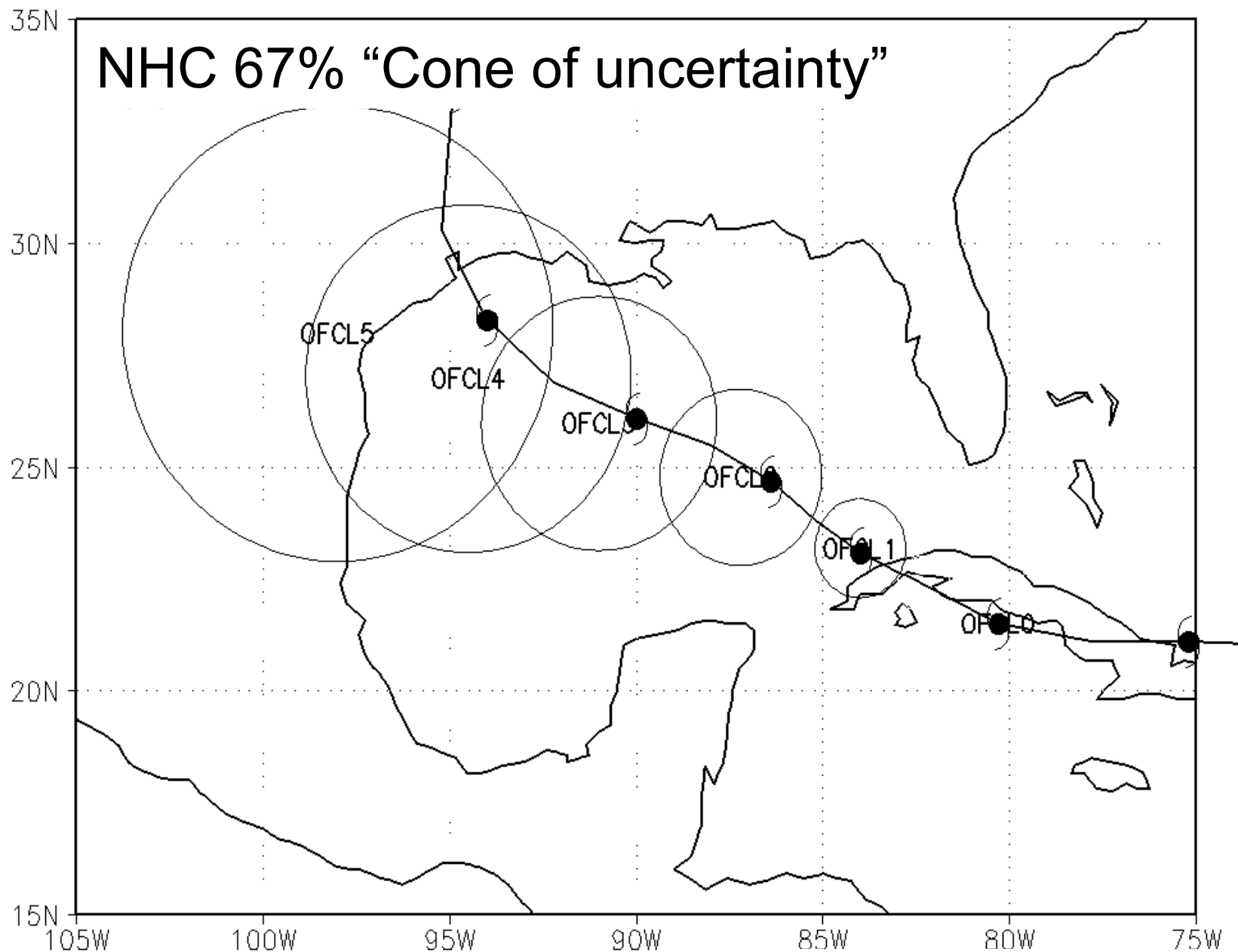
**Upper-level ridging developed downstream over SE U.S.**

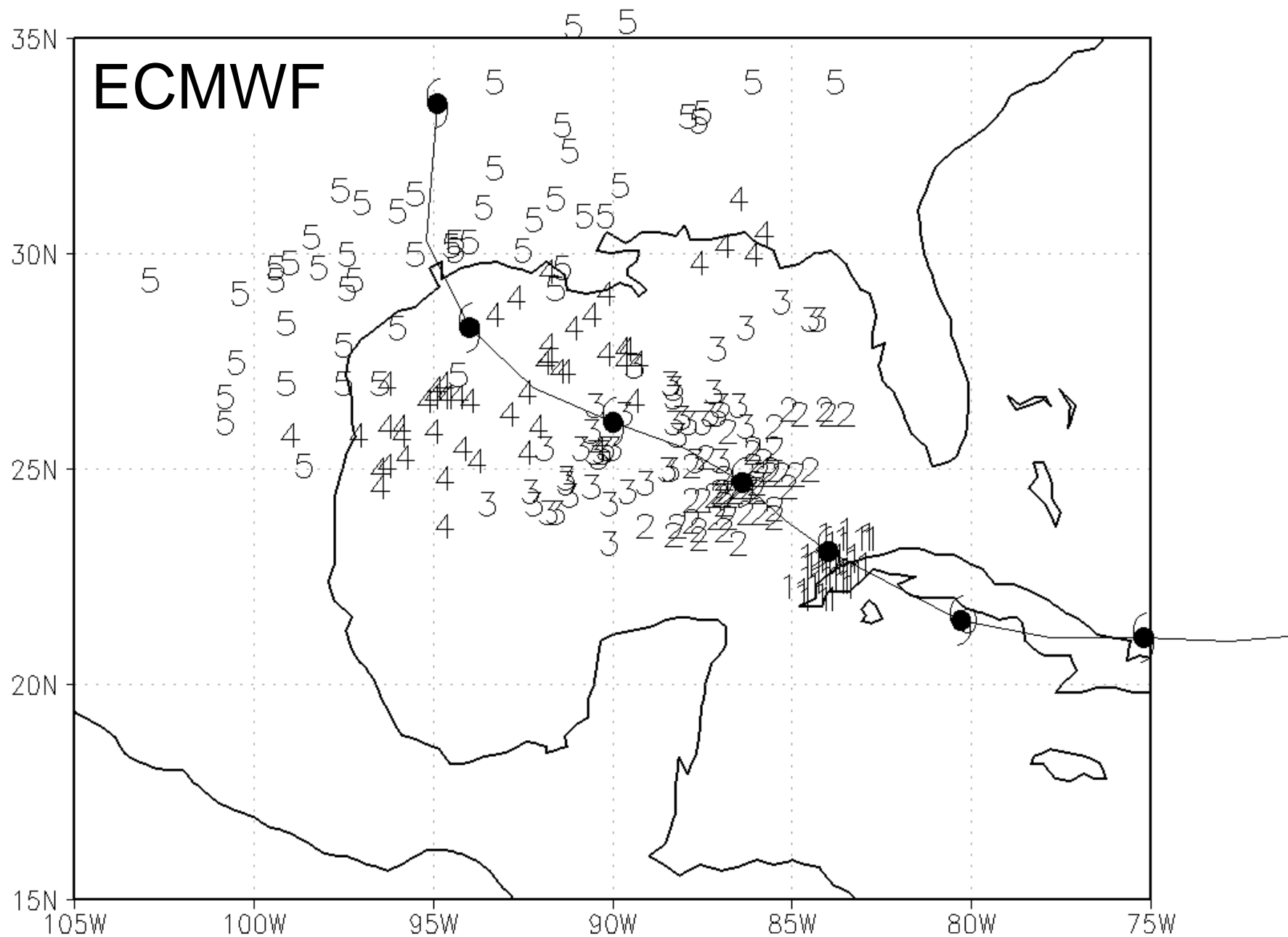
**Strong jet developed over SW U.S. by 13 Sep, setting the stage for Ike's rapid recurvature after landfall in SE TX.**

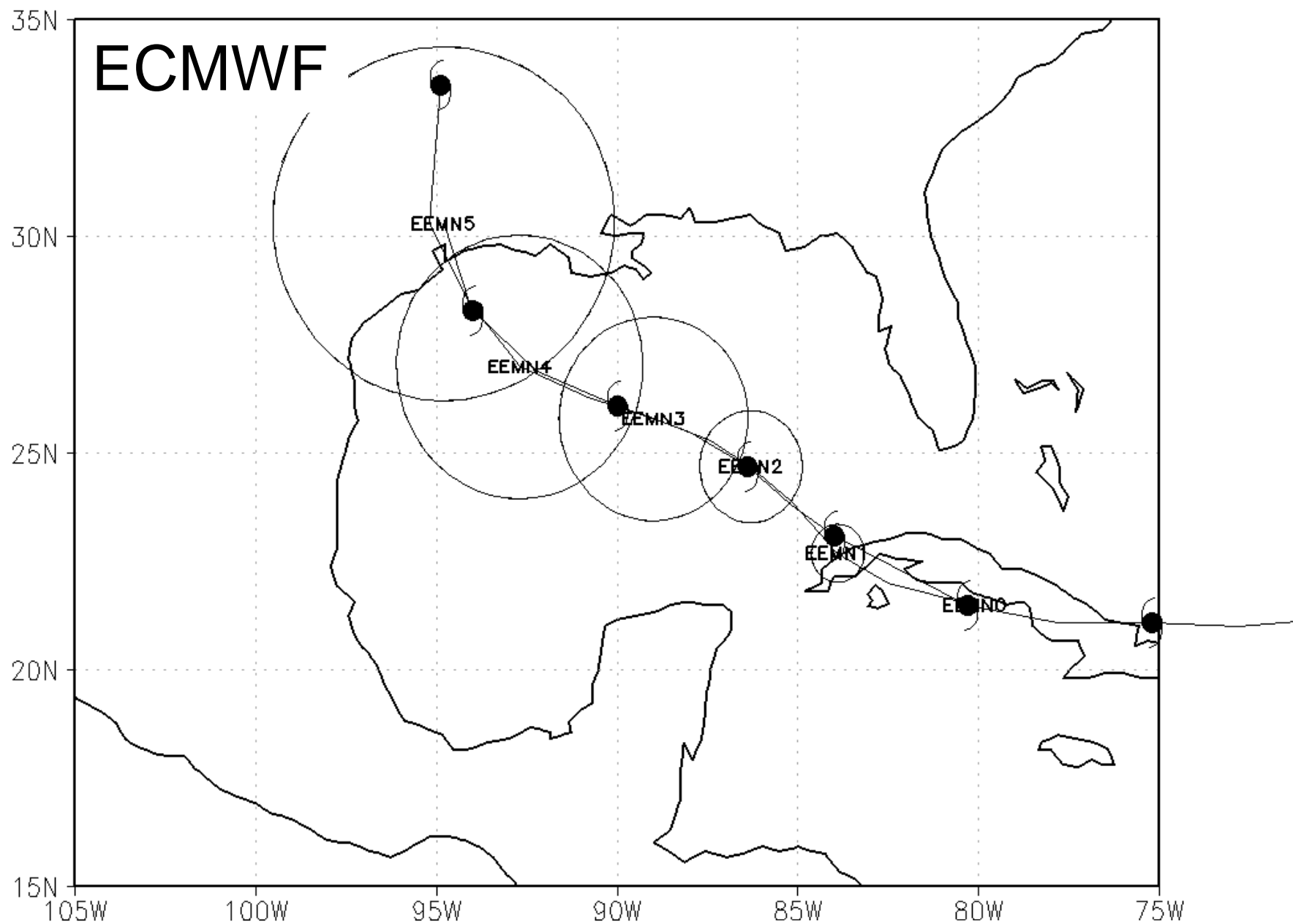


# Ike: Hypotheses

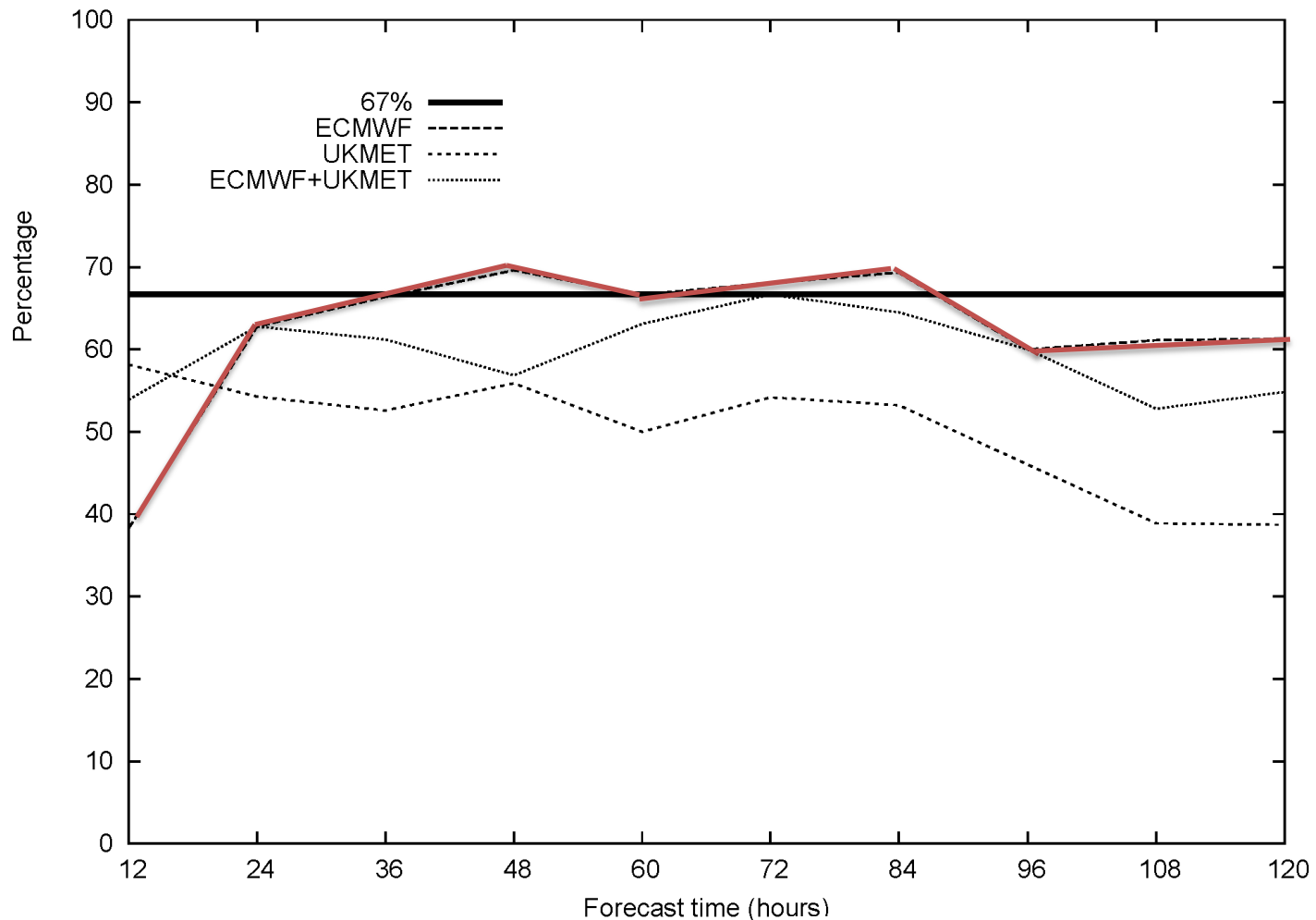
1. Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclone track.
2. Initial condition errors in the ridge and shortwave troughs were a primary reason for the troublesome landfall forecast.







# Over the full season, does the actual track fall within the 67% circles 67% of the time?



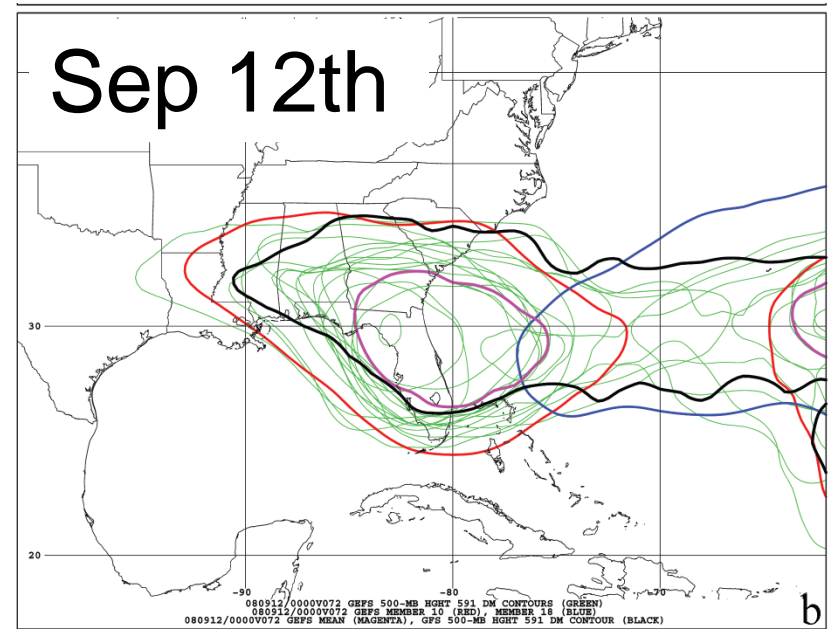
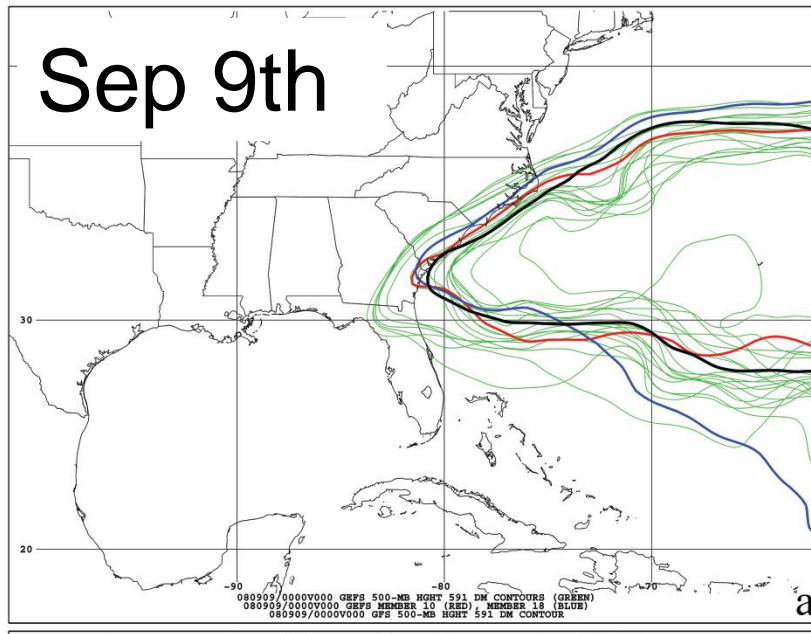
# Ike: Results 1

H: Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclone track.

- For the Atlantic season in 2008, in which the ensemble mean forecast was accurate, the ECMWF probability circles were also accurate. Not the case for NW Pacific in 2008.

# Ike: Hypotheses

1. Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclone track.
2. Initial condition errors in the ridge and shortwave troughs were a primary reason for the troublesome landfall forecast.



Low-predictability problem? Red and blue initial GEFS members produced similar 500 hPa Z on Sep 9<sup>th</sup>, but the red forecast exhibited a much stronger ridge on the 12<sup>th</sup>.

# NCEP GFS Assimilation experiments

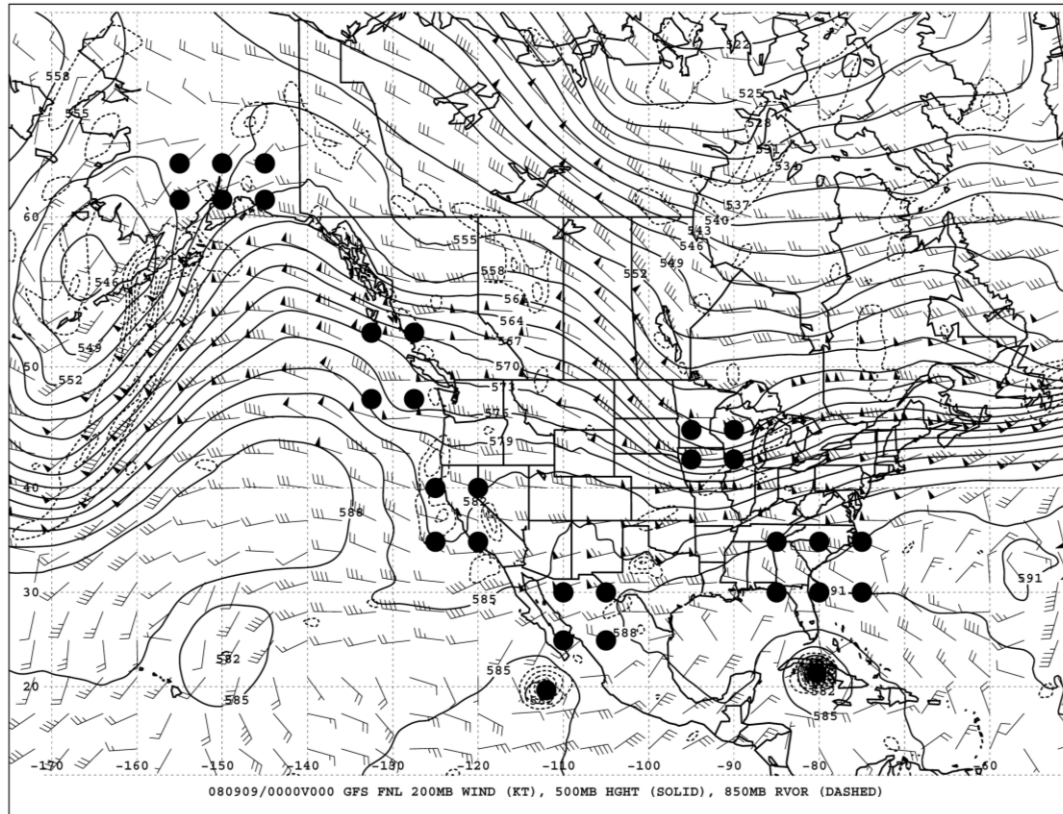


Figure 9. GFS analysis of 200-hPa wind (barbs, kt), 500-hPa geopotential height (solid contours, dam), and 850-hPa relative vorticity (positive values contoured every  $4 \times 10^5 \text{ s}^{-1}$ ) valid at 0000 UTC 9 September 2008. Dots represent the approximate location of observations for GFS perturbation experiments e1-e8.

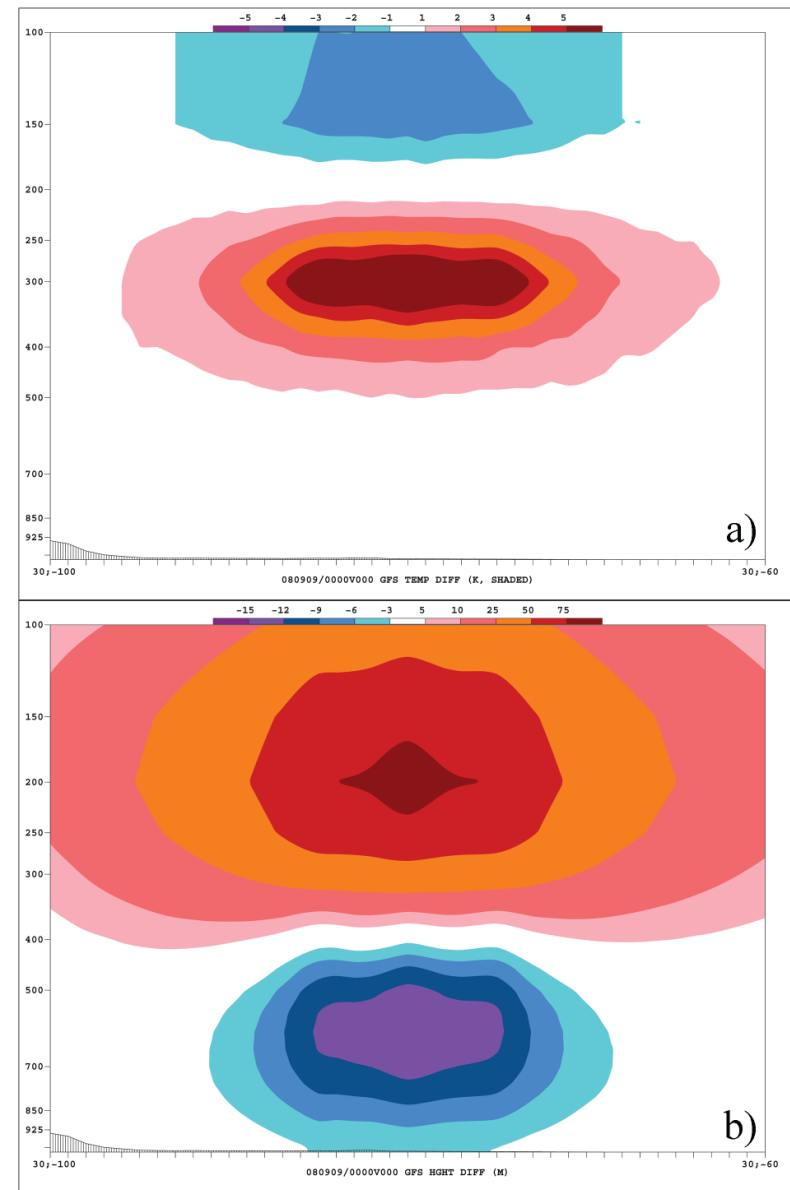


Figure 10. (a) Temperature perturbation (K) for experiment e1 along a cross section from 30°N 100°W to 30°N 60°W, (b) as in (a) except for geopotential height (m).

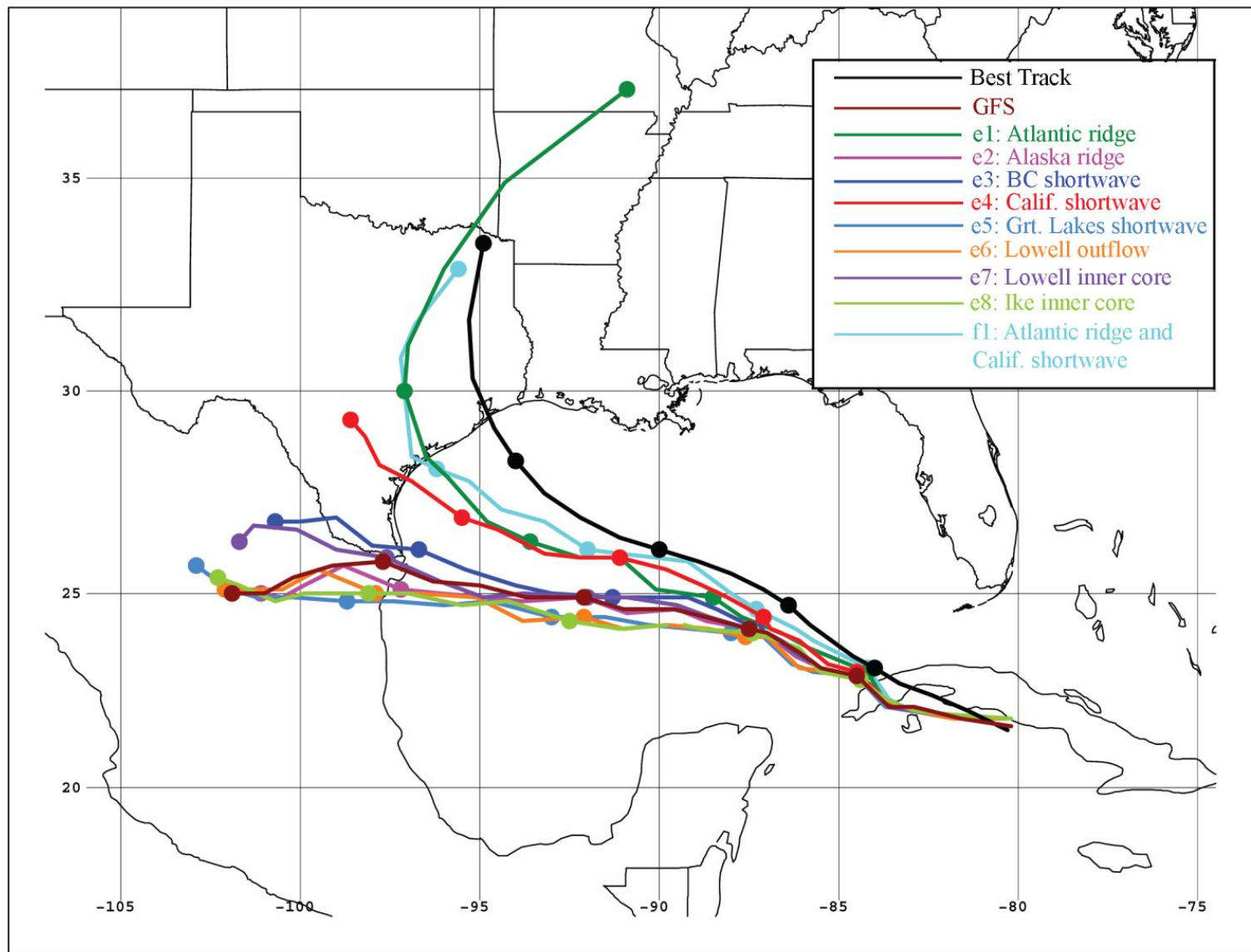


Figure 11. 5-day GFS track forecasts of Hurricane Ike initialized at 0000 UTC 9 September 2008, for the operational forecast (maroon), the eight perturbed analyses e1-e8, and the analysis ‘f1’ from the combined perturbations of the ridge north of Ike and the shortwave off California (see legend). The observed best track of Ike is shown in black. The dots along the tracks correspond to positions every 24 h during the forecast period.

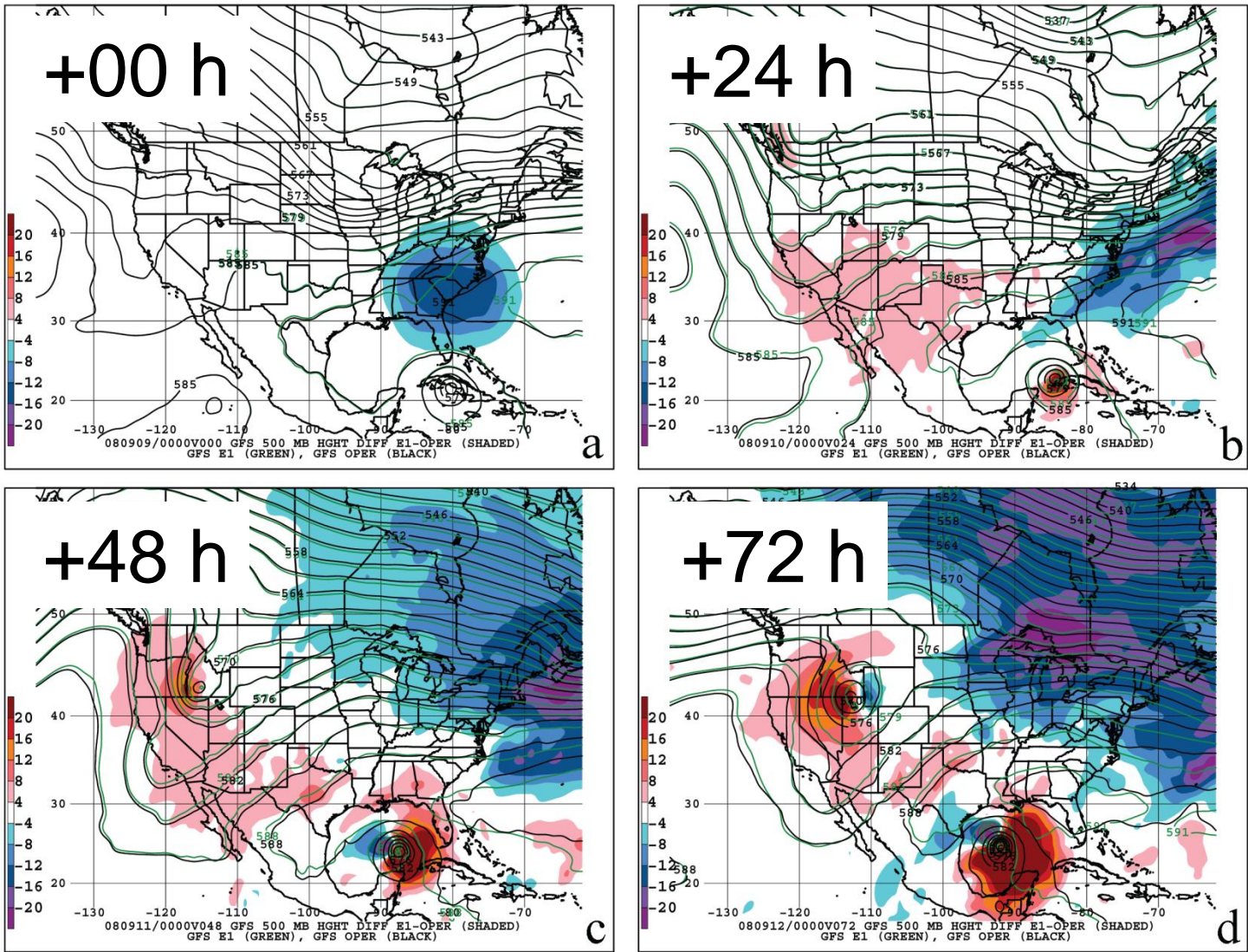
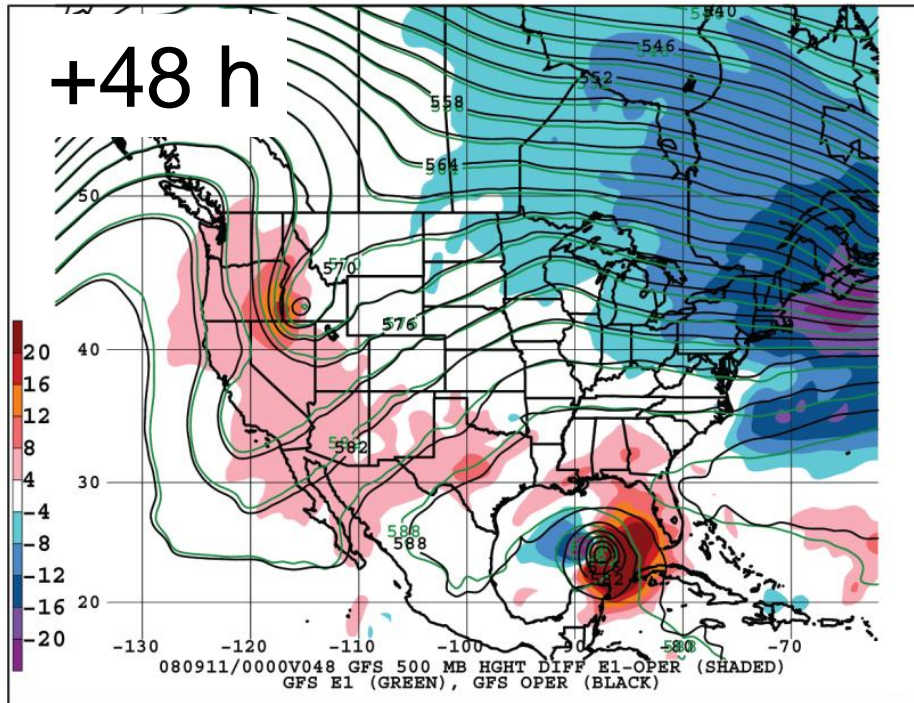
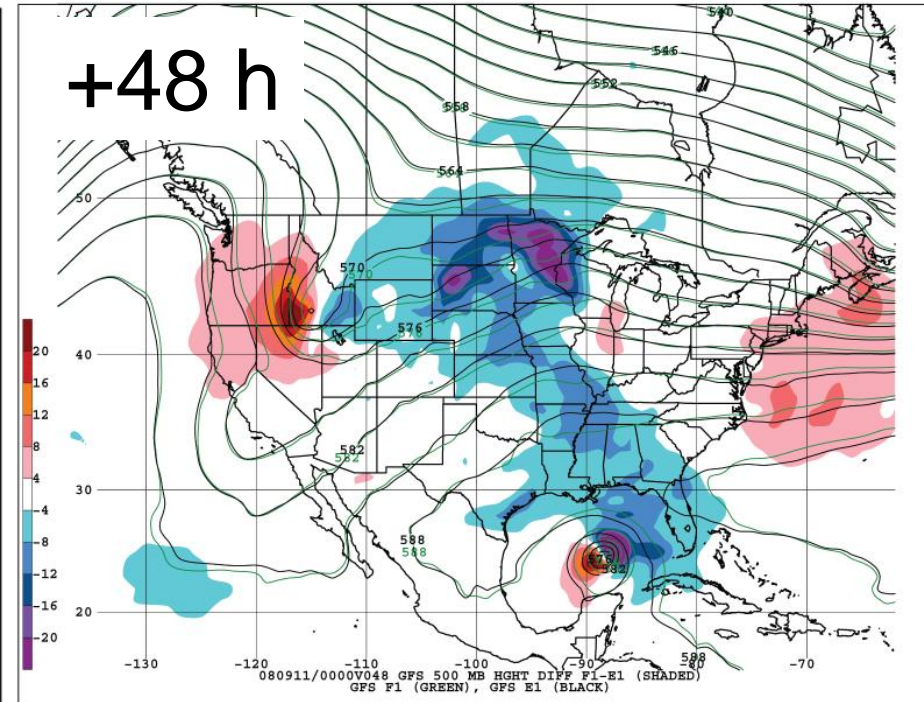


Figure 12. GFS 500-hPa geopotential height (contours, dm) from operational run (black) and perturbation experiment e1 (green) initialized at 0000 UTC 9 September 2008 and difference field e1-operational (shaded, m) for (a) the analysis (b) 24-h forecast, (c) 48-h forecast, and (d) 72-h forecast.

## Ridge only



## Add CA shortwave increment



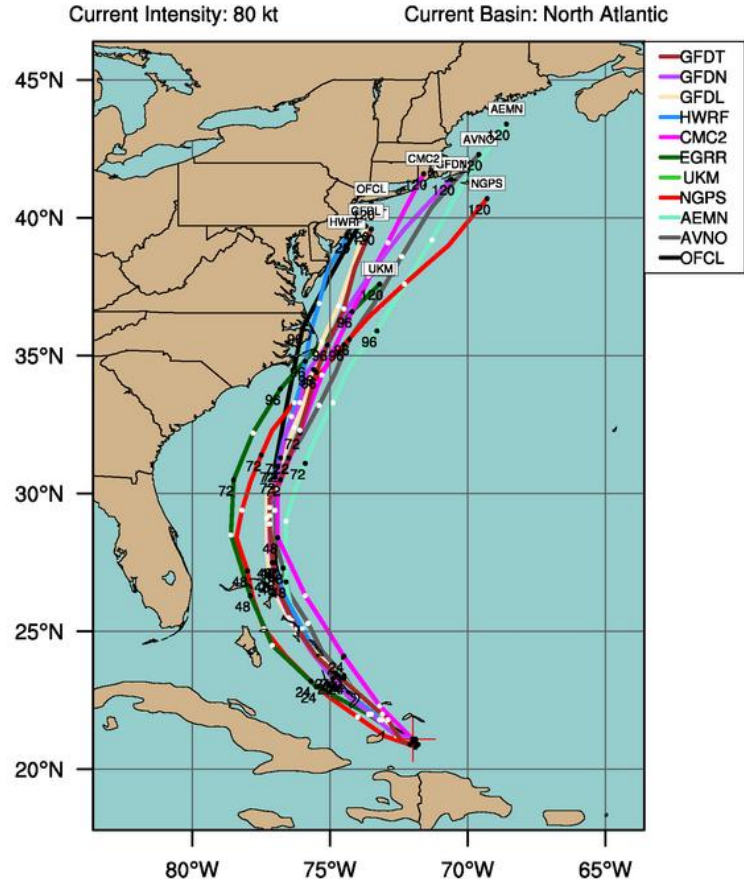
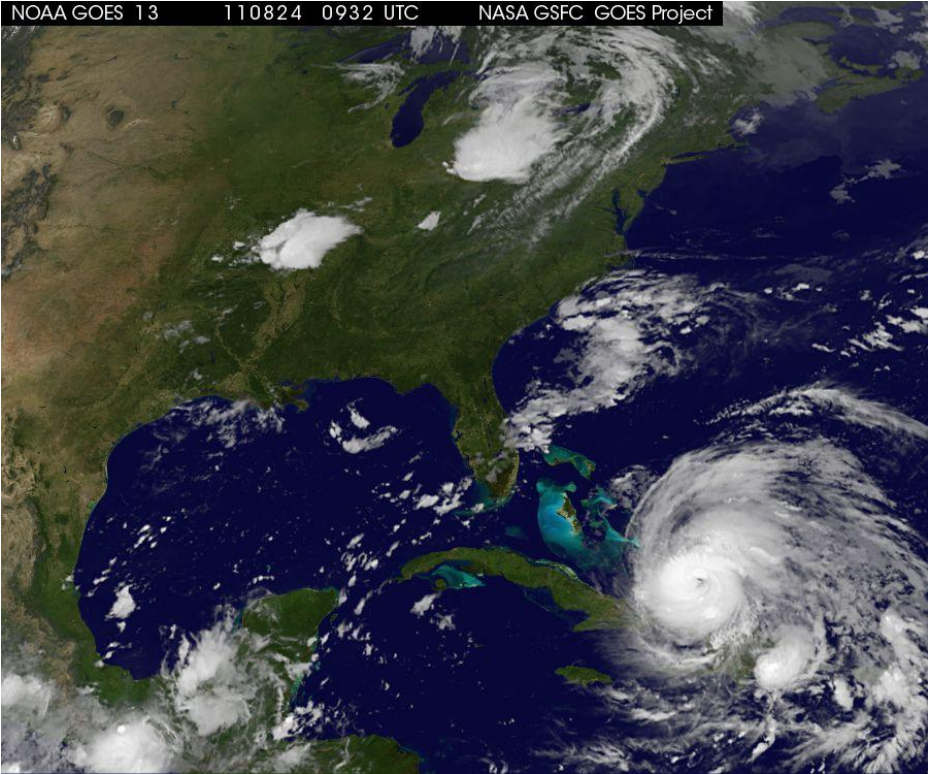
- A modest change to the operational analysis can modify the longwave pattern.
- Strengthened CA shortwave weakened ridge further, allowing Ike to gain more latitude.

# Ike: Results 2

H: Initial condition errors in the ridge and shortwave troughs were a primary reason for the troublesome landfall forecast.

- Weakening the ridge allowed Ike to gain in latitude, and thereby undergo recurvature.
- The strengthening of upstream troughs acted to modify the longwave pattern, further weakening the ridge adjacent to Ike.
- Some dependence on the model and perturbation method.

# Hurricane Irene (2011)

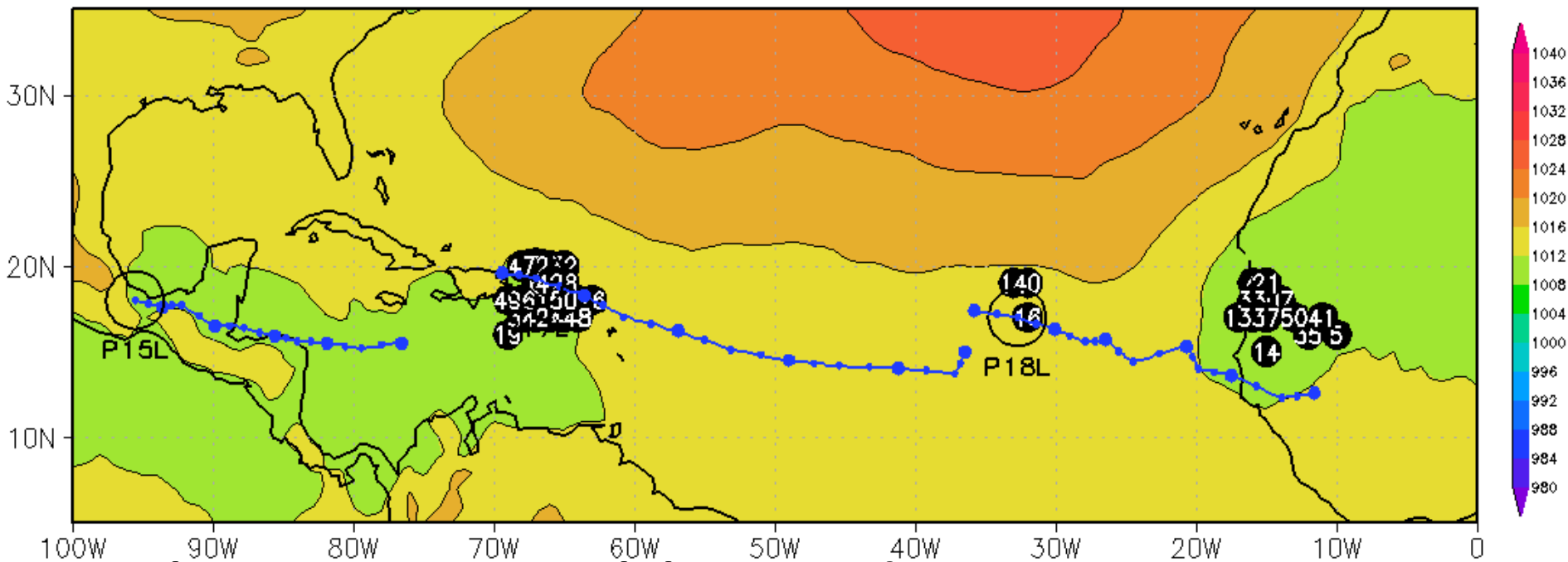


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# Irene: Hypotheses

1. Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclogenesis.
2. The assimilation of supplementary rawinsonde and dropwindsonde data improved the track forecast – ongoing work

Shading: ECMWF 108-hour CTRL MSLP. Init. 2011081800, Valid 2011082212.  
Dots: Ensemble members with MSLP < 1010 hPa and satisfying tracker criteria. 50 mem.



## Real-time ensemble products, Aug-Sep 2011

<http://www.rsmas.miami.edu/personal/smajumdar/predict/>

**Seek a reliable quantitative metric for a tropical cyclone**

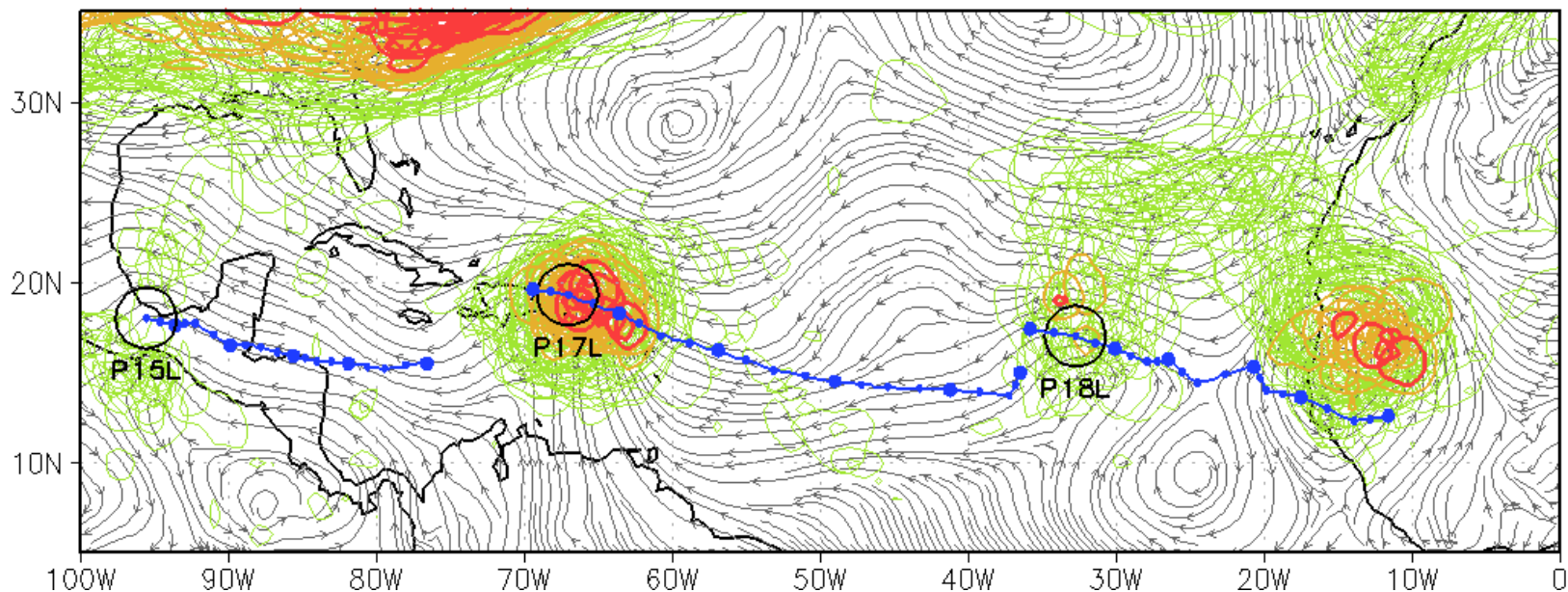
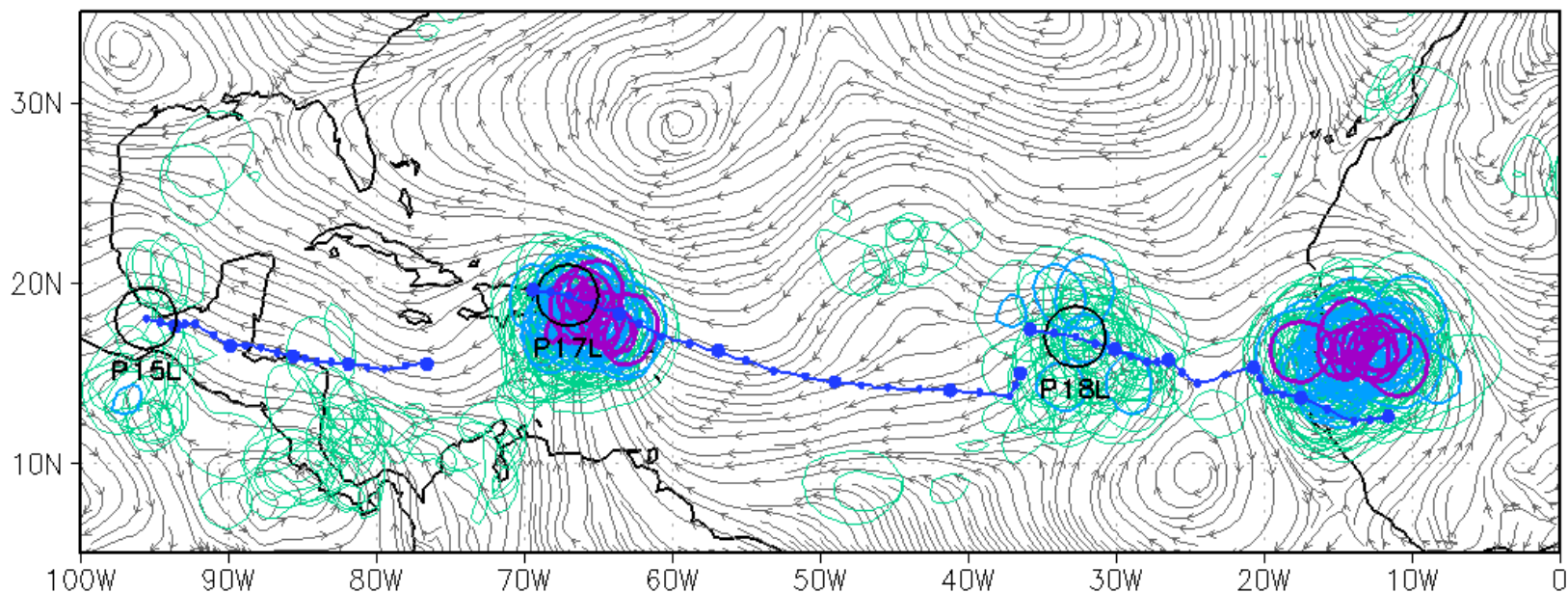
Area ave. rel. vort.  $> 5 \times 10^{-5} \text{ s}^{-1}$

Local 200-850 hPa thickness anomaly  $> 40 \text{ m}$

Local MSLP minima  $< 1010 \text{ mb}$

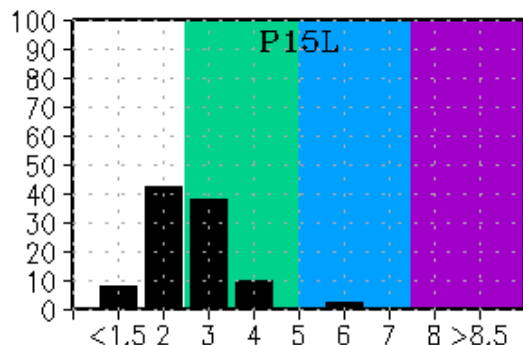
w/ Ryan Torn (SUNY at Albany)

Gray: ECMWF 108-hour CTRL streamlines of 700–850 hPa ave wind. Init. 2011081800, Valid 2011082212.  
Color: 700–850 hPa AREA-AVG REL. VORT.  $\times 2.5e-5 \text{ s}^{-1}$  and 200–850 hPa THICK ANOM  $\times 20 \text{ m}$ . 50 members.

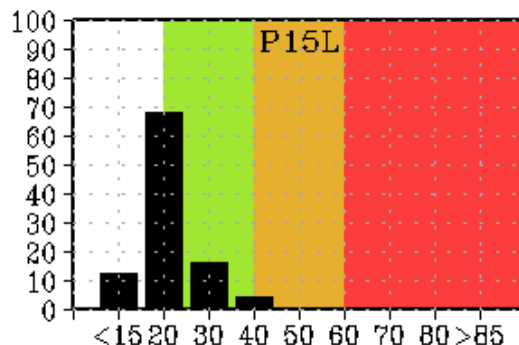


50-member ECMWF ensemble 108-hour forecast probabilities. Init. 2011081800, Valid 2011082212.

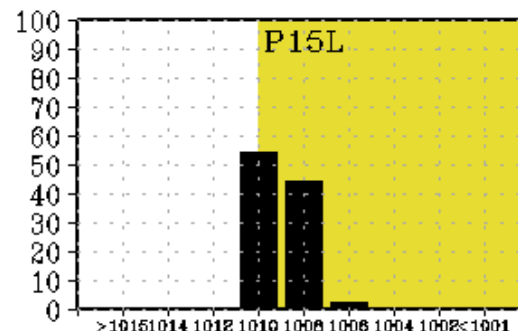
700-850 hPa AVE. REL. VORT.



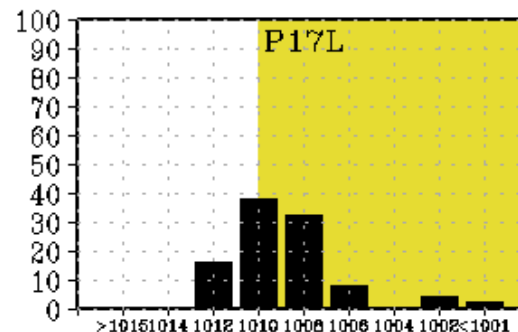
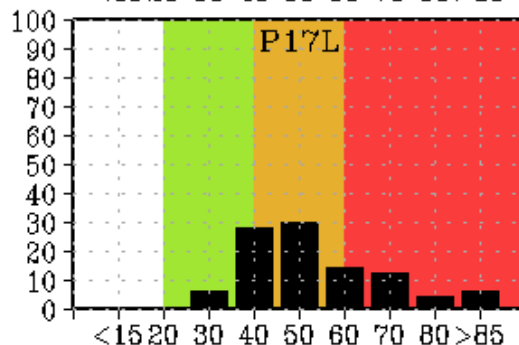
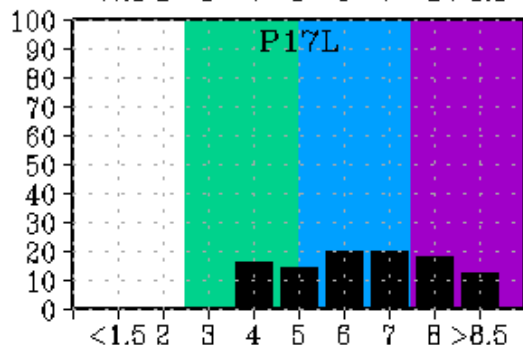
200-850 hPa THICKNESS ANOMALY



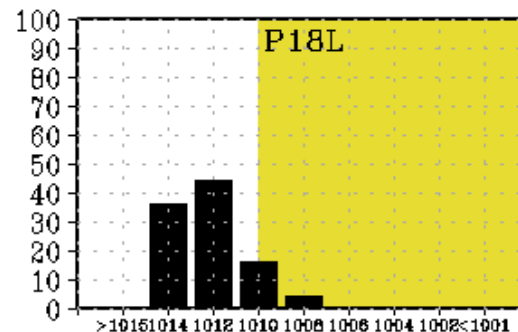
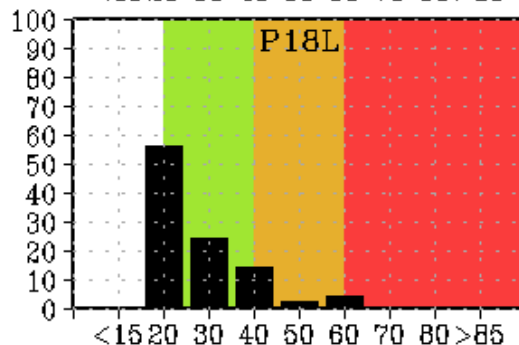
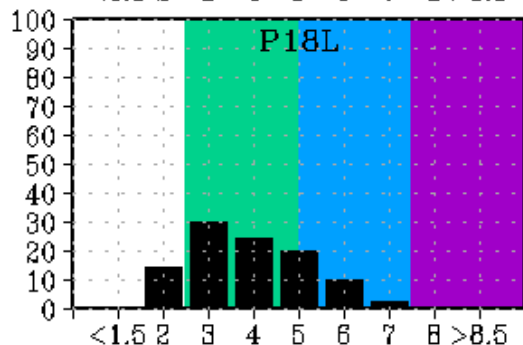
MSLP



0%  
Probability  
of TC



56%  
Probability  
of TC



6%  
Probability  
of TC

# Irene: Preliminary Results 1

H: Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclogenesis.

A quantitative metric for tropical cyclogenesis in numerical models is achievable.

Immediate future: Probabilistic verification of genesis and non-genesis cases, for 0-10 day ensemble forecasts in 2010-11.

# Ongoing and further work

- Danielle/Earl (2010): Track forecasting issues.
- Characteristics of forecast errors in genesis / non-genesis cases; quantifying predictability.
- Assimilation of satellite wind data and T and q soundings in global and regional models.
- Targeting strategies for satellite and rawinsonde / dropsonde data, particularly winds and moisture.
- Coordinated motion of unmanned aircraft and ensemble-based serial adaptive sampling.
- Environmental interactions; multiple scales.